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**Recommendations and Requirements for Welding
and Inspection of Titanium Piping for U.S. Navy
Surface Ship Applications**

by

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ADMINISTRATIVE INFORMATION

This report was prepared as part of the Titanium Welding Program under the sponsorship of Mr. Steve Linder, Director, Manufacturing Technology, ONR Code 361. The work was supervised by Mr. Robert DeNale, Head, Welding and NDE Branch, NSWC Carderock Division Code 615.

1.0 BACKGROUND

The 90/10 copper-nickel (Cu-Ni) alloy has served as the standard material of construction for seawater cooling and piping systems on U.S. Navy surface ships. Although this alloy has provided acceptable performance in many sections of these seawater-handling systems, other areas of these systems have been plagued with continued and often accelerated failure. Numerous cases of seawater system failures on newly commissioned Aegis cruisers and destroyers are blatant examples of the limitations of 90/10 Cu-Ni as a seawater alloy [1]. Included in these limitations is a susceptibility to erosion/corrosion from high flow velocities or turbulence, sulfide corrosion, impingement erosion-corrosion from air-laden seawater and crevice corrosion under marine deposits [1,2].

Titanium possesses a unique set of corrosion properties that favorably impacts current Navy ship design requirements for increased reliability and reduced maintenance in surface ship seawater systems. The excellent corrosion and erosion resistance of titanium derives from the formation of a very stable, transparent, and highly adherent surface oxide film. Because titanium is highly reactive and has an extremely high affinity for oxygen, the surface oxide film forms spontaneously and instantly when fresh metal surfaces are exposed to air and/or moisture. A mechanically damaged oxide film can re-heal itself instantaneously if at least traces (parts per million) of oxygen or water are present in the environment. Although the TiO_2 film is typically less than 10nm thick, the oxide imparts exceptional resistance to titanium against corrosion in seawater and exceptionally high resistance to seawater flow, impingement, turbulence and cavitation.

Of all the titanium alloys commercially available, the unalloyed or commercially pure (CP) group is considered to be the most resistant to corrosion in seawater. CP titanium has a predominantly alpha microstructure at room temperature and is not heat treatable. CP titanium is normally produced to requirements of American Society for Testing and Materials (ASTM) standard specifications in grades 1, 2, 3, and 4. These grades vary in oxygen and iron content, which control the strength level and corrosion resistance. Some CP grades also contain small additions of palladium (grade 7 and 11) or nickel and molybdenum (grade 12) for improved resistance to crevice corrosion at elevated temperatures. For most seawater corrosion applications, grade 2 is selected for its wide availability, moderate strength level and good formability [3]. The corrosion properties of Ti-CP, grade 2 in seawater include [4-7]:

- Immunity to general corrosion in polluted, stagnant, de-aerated seawater, aerated seawater and hypo-chlorinated seawater at temperatures below 200° F;
- Immunity to pitting and crevice corrosion below 160° F;
- Immunity to stress corrosion cracking;
- Immunity to hydrogen embrittlement at temperatures below 175° F;
- Resistance to erosion/corrosion attack at velocities up to 15-18 ft/sec in silt-laden seawater, and above 100 ft/sec in silt-free seawater;
- Immunity to galvanic corrosion; *
- Weld and base materials having similar mechanical and corrosion properties in seawater.

* Titanium will galvanically simulate corrosion of more active metals in the same seawater system to an extent similar to that of stainless steel alloys. Several methods are available to protect other metals in the piping system from galvanic corrosion, including protective coatings (applied to the titanium), electrical isolation, and cathodic protection.

The Navy has utilized the seawater erosion and corrosion resistance of CP titanium in a number of seawater cooling replacement applications. For example, Ti-CP, grade 1 and 2 heat exchangers have replaced 90/10 copper-nickel for both direct and indirect cooling of shipboard machinery and electronic coolers. Titanium seawater coolers have also been incorporated in both the low and high-pressure air compressor units on newer combatants such as the LHD Amphibious Assault Ships and DDG-51 Aegis Guided-Missile Destroyers. More recently, the Navy has identified Ti-CP, grade 2 for the low pressure, class P-2 piping system on the new LPD-17 Amphibious Transport Dock ship class. The use of titanium for the seawater service and firemain systems on this ship class represents the first major application of this material in a new ship design.

As the use of welded titanium piping components in Navy shipbuilding is expected to increase for both corrosion and structural efficiency reasons, it was recognized that a guide to titanium pipe welding would be of benefit to both Navy and shipyard/contractor personnel. The objective of this report is to provide a single source reference for requirements, recommendations and guidance information on CP titanium pipe welding and inspection for U.S. Navy surface ship construction.

2.0 INTRODUCTION

In general, titanium can be welded using techniques similar to those employed for gas tungsten arc welding of other high performance naval materials such as stainless steels and nickel base alloys. However, titanium is a reactive material and additional precautions are required to produce a sound weld. There are two fundamental differences that must be understood prior to making satisfactory welds in titanium and titanium alloys.

First, titanium will absorb interstitial elements such as oxygen, and to a lesser extent hydrogen and nitrogen, from the surrounding atmosphere at temperatures above about 840° F. The absorption of interstitial elements will increase the strength and hardness of the weld and heat-affected zone (HAZ) at the expense of the ductility and toughness. These reactions are particularly rapid when titanium is molten; hence, the weld pool is most vulnerable to embrittlement. Contamination of the liquid puddle will result in through-thickness embrittlement of the solidified weld. Contamination of the solidified weld bead and HAZ will produce a hardened surface layer with poor surface ductility and toughness. Interstitial contaminants such as oxygen and nitrogen cannot be removed from the weld, and hydrogen can be removed only by vacuum annealing.

Second, molten titanium reacts strongly with practically all materials, including refractories and carbon, particularly if the latter is present on the joint surfaces as grease, oil or other carbonaceous compounds. These reactions will form brittle compounds that will impair the ductility and toughness of the welded joint. For example, particles of steel on the surface of titanium adjacent to the fusion line of a weld will alloy with the titanium to give small regions of high iron concentration. These regions will be brittle and, in some environments, susceptible to corrosion.

The above differences require that the liquid puddle, solidified weld and adjacent material on both the inside and outside of the pipe be completely shielded with inert gas to prevent atmospheric contamination at welding temperatures. Equally important, the parts to be welded must be meticulously cleaned of mill scale, oil and grease from machining and forming operations, dust, dirt, moisture and other potential contaminants. Contamination of the weld caused by inadequate cleaning of the joint and filler materials, impurities in the shielding gas and inadequate gas shielding has the potential to significantly increase welding costs from the labor-intensive removal, repair and re-inspection of the weld.

The following sections provide recommendations, requirements and guidance information on quality assurance, materials, welding area, welding process, welding equipment, orbital pipe welding systems, gas shielding, weld joint design, joint preparation, pre-weld cleaning, joint fit-up and tacking, welding technique and visual inspection to produce sound welds in CP titanium seawater piping systems. The fabrication requirements contained in this report are taken from NAVSEA technical publication S9074-AR-GIB-010/278 *Requirements for Fabrication Welding and Inspection, and Casting Inspection and Repair for Machinery, Piping, and Pressure Vessels* [8]. The mandatory requirements, as indicated by the word "shall," are considered to be the minimum acceptable for first quality workmanship. Recommendations and guidance information are not considered mandatory.

3.0 QUALITY ASSURANCE

The quality assurance and welding qualification provisions for CP titanium piping are similar to those for most other materials. The shipyard *shall* establish a quality control system that consists of approved inspection and audit procedures, and maintenance of records that will assure the Government that welded titanium piping systems conform to all of the requirements contained in technical publication S9074-AR-GIB-010/278 [8]. Written procedures *shall* be prepared by Quality Assurance that assigns responsibility and accountability for performing these inspections.

3.1 MATERIAL CONTROL

3.1.1 Receipt Inspection and Identification

In a shipyard, there are generally two functions that are responsible for receipt inspection; Material Control and Quality Assurance. Material Control is responsible for the verification that delivered items are received in accordance with the purchase orders. Material Control personnel *shall* examine incoming titanium materials to ensure that the individual deliveries are properly documented, contain the correct quantity, are suitably identified, and are properly packaged and protected.

Quality Assurance is responsible for the verification that delivered materials are physically and technically in accordance with the procurement specifications. Quality Assurance personnel *shall* perform a physical and technical inspection of incoming titanium piping materials. Physical inspection covers the packaging, damage, finish, identification, and marking of titanium materials. Technical inspection covers verification of the material grade relative to the identification and material marking. Quality Assurance *shall* perform random sampling of the

received materials to ensure the specified grade meets the chemical and mechanical property requirements of the procurement specification. Quality Assurance *shall* also inspect all consumables used in fabrication of titanium piping systems including shielding gases, cleaning solvents and dye penetrants. All materials *shall* be certified by Quality Assurance for purity and conformance to specifications and/or fabrication plan. Written records of the inspection results *shall* be maintained by the shipyard/contractor.

An identification system *shall* be established and maintained by Quality Assurance, which includes the specification number and grade of titanium piping components. Although industrial fabricators generally color code the titanium piping materials, it is recommended that as part of the identification system each titanium component carry an identification label and receipt inspection number. Welding rods and spooled wire should carry an identification label and receipt inspection number on each container. Each piece of bare rod used for manual welding should have a distinguishable identification tag or label. Identification of titanium piping materials *shall* be maintained by Quality Assurance to the point of usage. Quality Assurance *shall* visually verify that the material identification corresponds to the material specified on the drawing or fabrication document at the initial point of fabrication. Finally, Quality Assurance *shall* perform periodic internal audits of the inventories, stocking facilities and shops to ensure that titanium materials are correctly identified.

3.1.2 Material Storage

The storage of titanium piping materials should be covered by a written procedure developed by Quality Assurance and implemented by Material Control. It is recommended that all titanium base and filler materials be stored inside to keep the materials clean and dry. All materials should be protected from contact with non-titanium materials. Piping should be stored horizontally on racks that are located in a clean area, away from where dirt and grit can accumulate. All filler materials *shall* be stored in their original closed containers for protection from moisture, dirt and dust until used. Quality Assurance *shall* perform periodic inspections of storage facilities.

3.1.3 Material Handling

Quality Assurance *shall* develop written procedures to ensure that titanium materials are handled to avoid inadvertent contamination from abrasive debris, dirt and grit. All personnel working with titanium *shall* be given instruction by Quality Assurance on these procedures. This includes riggers, grinders, machinists, pipefitters, welders, nondestructive evaluation personnel, inspectors and engineers. Records of personnel training *shall* be maintained and reviewed by Quality Assurance to ensure qualifications are current. A training plan, including methods of review to ensure continuous compliance, *shall* be prepared by the shipyard and submitted to NAVSEA for approval.

3.2 RECORDS

The piping class dictates the requirements for written records. It is recommended that Quality Assurance prepare and maintain records for the low pressure class P-2 titanium piping systems as currently required for each titanium weld in piping classes P-1 and P-LT that undergoes nondestructive inspection. For each welded joint in classes P-1 and P-LT, the record form *shall* include information on (a) joint identification, (b) joint design, (c) base material type and identification, (d) filler metal type and identification, (e) fit-up, (f) welding procedure identification, (g) heat treatments, (h) welder identification, (i) NDT methods and results, (j) disposition of welds, (k) cycles of repairs to welds, (l) inspection procedures and (m) NDT personnel identification. For items (a) to (h) above, the record form *shall* be signed and dated by production or inspection personnel. For the remaining items, the record form *shall* be signed or stamped only by a qualified NDT person, except for visual examination of the root pass at 5X, which may be performed by qualified production personnel. An additional inspection record signed and dated by production or inspection personnel is required for each titanium weld or weld repair in titanium base metals that includes the following:

- Verification that the weld joint was cleaned before welding and that inert shielding and purge gas of the required dew point was used;
- Identification of the welders for each pass. Results of the in-process color inspection and the responsible welder's (or inspector's) signature and date;
- Identification of any pass that failed the visual inspection and how that pass was repaired;
- Postweld heat parameters, if applicable.

These records *shall* be maintained by the shipyard through the life of the contract and for three years after delivery. Disposition of records three years after delivery *shall* be as agreed upon by NAVSEA and the shipyard/contractor.

3.3 WELDING QUALIFICATION

Prior to making production welds in titanium piping systems, welding procedures and welders *shall* be qualified in accordance with the requirements of technical publication S9074-AQ-GIB-010/248[9]. Welding procedures *shall* be prepared by the shipyard/contractor in accordance with the requirements contained in Section 4 of technical publication S9074-AQ-GIB-010/248[9]. Procedure qualification weldments *shall* be prepared in accordance with the proposed procedure and evaluated by nondestructive and destructive tests. The welding procedure and procedure qualification data *shall* be submitted to NAVSEA or its authorized representative for review and approval prior to production welding.

Welders and welding operators *shall* be qualified in accordance with the requirements contained in Section 5 of technical publication S9074-AQ-GIB-010/248[9]. As a prerequisite to performance qualification, each titanium welder *shall* be trained and tested in workmanship standards and visual inspection requirements contained in technical publication S9074-AR-GIB-010/278 [8]. The training program *shall* be approved by one of the activity's MIL-STD-271 certified Level III nondestructive test examiners. A copy of the training procedure *shall* be submitted to NAVSEA or its authorized representative for approval. Additional information on welder training is contained in Section 5.2.3.1 of technical publication S9074-AQ-GIB-

010/248[9]. Performance qualification weldments *shall* be prepared and evaluated by nondestructive and destructive tests. The performance qualification data *shall* be submitted to NAVSEA or its authorized representative for approval. It is noted that welders qualified for in-chamber welding of titanium *shall* be re-qualified for welding outside of a chamber. Welders qualified for out-of-chamber welding of titanium *shall* be trained in chamber operation prior to chamber welding.

In addition to an annual vision test, each titanium welder and welding operator *shall* pass an annual color perception test on workmanship samples representative of the surface colors expected in titanium welding. As a minimum, these colors include silver, straw, purple, dark blue, light blue and gray. Welders and welding operators who fail the color perception test *shall* not be permitted to weld titanium. Additional information on vision test requirements is contained in Section 5.2.12 of technical publication S9074-AQ-GIB-010/248[9].

3.4 NDT PERSONNEL

All NDT procedures and personnel working with titanium piping *shall* be qualified in accordance with the requirements of technical publication T9074-AS-GIB-010/271[10]. Visual inspection of titanium welds for surface color *shall* be performed using a written procedure prepared by Quality Assurance and qualified visual inspectors. VT inspectors *shall* be qualified for color inspection prior to initial examination of titanium materials. In addition, visual inspectors *shall* pass a color perception test based on workmanship samples displaying the colors and shades representative of titanium welds contaminated by atmospheric elements. As a minimum, these colors *shall* include silver, straw, purple, dark blue, light blue and gray.

3.5 ADDITIONAL REQUIREMENTS FOR WELDING TITANIUM

Additional quality assurance requirements are provided in Appendix A of technical publication S9074-AR-GIB-010/278 [8]. This appendix requires that the shipyard prepare a fabrication plan that addresses fabrication and quality assurance controls, facility requirements, personnel training and production testing of titanium weld coupons. This information *shall* be submitted to NAVSEA for approval prior to production welding. The requirements that constitute this document have either been reviewed or will be reviewed in the following sections of this report. To assist the shipyard/contractor in preparation of this document, a fabrication plan shell is provided in Appendix A of this report.

4.0 MATERIALS

4.1 BASE MATERIALS

4.1.1 Classification

Four grades of CP titanium are currently permitted for use in seawater piping systems on U.S. Navy surface ships. Unless otherwise approved by NAVSEA, these grades *shall* conform to ASTM classifications 1, 2, 3, and 7. They are covered by the latest edition of ASTM B861 [11]* for seamless pipe, B862 [12]* for welded pipe and B363 [13] for fittings. These specifications identify the grade, pipe dimensions and tolerance, manufacturing method, finish, identification, marking and packaging requirements for the material. It is recommended that the purchase order stipulate that all titanium pipe be furnished in the annealed condition, along with a certification test report that provides the results of chemical analyses and mechanical property tests. Procurement of welded pipe to B862 should also invoke at a minimum the spot radiography supplementary requirement.

The chemical and mechanical property requirements from B862 are provided in Tables 1 and 2, respectively, for information. (The requirements for B861 and B363 are the same as those for B862). The CP grades listed in Table 2 are classified by chemical composition, which provides various combinations of strength and ductility. Grade 1 possesses the highest purity, lowest strength and best room temperature ductility. As the impurity level of oxygen and iron increases from grade 1 to grade 3, the strength increases and the ductility decreases. Ti-CP, grade 2 is the most common and widely used grade for both industrial and Navy corrosion-resistant seawater system applications with an ASTM guaranteed minimum yield strength of 40 ksi and good ductility and cold formability. Grade 7 has the same oxygen and iron content as grade 2, and hence, the same mechanical properties, but is modified with small additions of palladium for improved resistance to crevice corrosion at low pH and elevated temperatures (500° F).

Table 1. Chemical composition requirements of base materials.

Element	Composition, weight percent			
	Gr. 1	Gr. 2	Gr. 3	Gr. 7
Nitrogen, max	0.03	0.03	0.05	0.03
Carbon, max	0.10	0.10	0.10	0.10
Hydrogen, max	0.015	0.015	0.015	0.015
Iron, max	0.20	0.30	0.30	0.30
Oxygen, max	0.18	0.25	0.35	0.25
Palladium				0.12-0.25
Residuals (each), max	0.1	0.1	0.1	0.1
Residuals (total), max	0.4	0.4	0.4	0.4
Titanium	remainder	remainder	remainder	remainder

Table 2. Mechanical property requirements of base materials.

* ASTM specification B337 listed in Table I of technical publication S9074-AR-GIB-010/278 [8] was discontinued in 1997 and replaced by specifications B861 and B862.

Mechanical Property	Gr. 1	Gr. 2	Gr. 3	Gr. 7
Tensile Strength, min, ksi	35	50	65	50
Yield Strength, min/max, ksi	25/45	40/65	55/80	40/65
Elongation, min, %	24	20	18	20
Product Designation*	Ti-35	Ti-50	Ti-65	Ti 50 with Pd
*Commercial brochures differentiate grades 1, 2, 3, and 7 by their minimum tensile strength.				

4.1.2 Sizes

Ti-CP seamless piping is commercially available in sizes up to 6 inches and lengths up to 40 feet. Welded pipe is available in 12-20 foot lengths and a full range of pipe diameters. While the low pressure piping systems on Navy ships will utilize schedule 10S, both types of pipe are provided down to the schedule 5S size. Heavier wall schedule 40S is also available in either seamless or welded form for high-pressure piping applications. Pipe wall thickness for each of these schedules from ASME B36.19 [14] is provided in Table 3 for information. From a cost standpoint, it is advisable to select the seam-welded product when smaller pipe sizes (at or below schedule 10S) are involved and as the pipe diameter increases. For example, the cost of grade 2 schedule 10S welded pipe is on the order of 30% less than the seamless product.

Table 3. Schedule 5S, 10S and 40S piping dimensions.

Nominal Pipe Size	Outside Diameter Inches	Nominal Wall Thickness, inches		
		Schedule 5S	Schedule 10S	Schedule 40S
1/2	0.840	0.065	0.083	0.109
3/4	1.05	0.065	0.083	0.113
1	1.315	0.065	0.109	0.133
1-1/4	1.660	0.065	0.109	0.140
1-1/2	1.900	0.065	0.109	0.145
2	2.375	0.065	0.109	0.154
2-1/2	2.875	0.083	0.120	0.203
3	3.5	0.083	0.120	0.216
3-1/2	4.0	0.083	0.120	0.226
4	4.5	0.083	0.120	0.237
5	5.563	0.109	0.134	0.258
6	6.625	0.109	0.134	0.280
8	8.625	0.109	0.148	0.322
10	10.750	0.134	0.165	0.356
12	12.750	0.156	0.180	0.375

Somewhat parallel cost relationships apply to titanium pipe fittings (elbows, tees and reducers). Titanium fittings are commonly available in most sizes, and are provided with either square or belled-end preparations suitable for welding. For nominal diameters equal to or less than 6-inches, fittings are most often produced from seam welded or seamless pipe stock. In these sizes, grade 2 elbows can be compression formed to tight bend radii of 1 or 1-1/2 D. Above 6-inch diameter all elbows and tees are fabricated using a clamshell approach; that is, the elbow is

formed in two halves and then the halves are welded together. Cast titanium fittings, although available, are generally not utilized because of cost.

Flange types include Type-A stub ends (with slip-on backer flange) and welding neck flanges, Figure 1. The Type-A stub-end is recommended since it is most readily available commercially and is approximately one-third the price of the welding-neck flange. Slip-on backer flanges can be steel, bronze or titanium depending on the corrosivity of the surrounding environment.

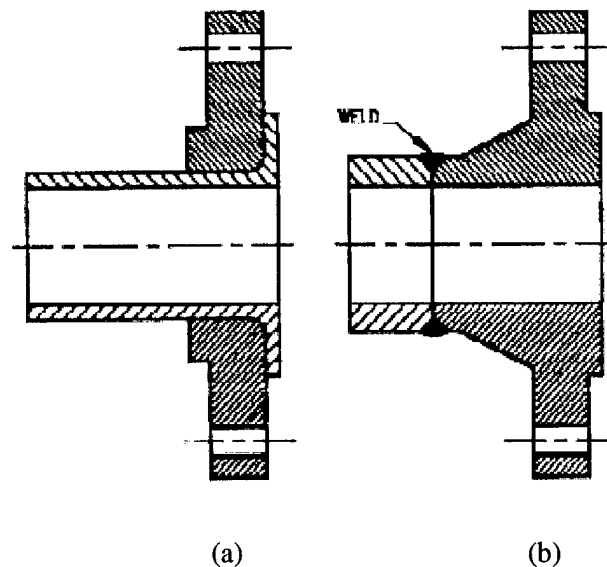


Figure 1. Type A stub end (a) and welding neck flanges (b).

4.1.3 Pipe Bending

Bending of Ti-CP pipe for U.S. Navy surface ship construction *shall* conform to the requirements of MIL-STD 1627 [15]. Bends in Ti-CP can be performed on the same equipment commonly used for bending stainless steel piping. However, all tooling used on the final surface, such as bending dies and mandrels, *shall* be cleaned with acetone or other approved solvent to remove grease, oil or other contaminants prior to use on titanium. Titanium is extremely reactive at elevated temperatures and titanium pipe should be cold bent only at a maximum temperature of 100° F. Ti-CP, grade 2 can be cold-formed to a minimum radius of 3 pipe diameters (3D bend) in pipe from 2- to 4 inches in diameter. Larger diameter pipe up to 8 inches may be cold-formed to a minimum radius of 2.5 pipe diameters (2-1/2D). It is noted that bends to a radius less than 5D will require procedure qualification in accordance with the requirements of reference 15.

Pipe-bending speeds should be maintained in the range of ¼ degree to 4 degrees per minute and a lubricant should be used. Lubricants used with titanium should not contain sulfur or chlorine in excess of 250 ppm. Pipe-bending lubricants for titanium should be restricted for use in cold bending only, unless demonstrated by the shipyard/contractor to have no detrimental effects at higher bending temperatures. Titanium tends to deform locally under tensile loading

during pipe bending. Material that will form the inside of the bend undergoes severe compression that is transmitted back toward the as yet unbent end of the pipe, where it can cause wrinkles. The formation of ripples along the inside of the bend can be eliminated by using mandrels with closely spaced balls to help support the inside of the pipe, and ensuring that the wiper die extends to within 1/8 to 1/2-inch of the tangent point. Titanium also has more spring-back than copper-nickel and bending machines must be set to compensate for it in bending of small diameter (< 2 inches) pipe. After forming, the surfaces of the pipe *shall* be cleaned in accordance with the requirements described in Section 12.0. Post-bending heat treatments of Ti-CP pipe are not recommended.

4.2 FILLER MATERIALS

4.2.1 Classification

Filler materials are covered by the American Welding Society (AWS). Each wire composition is identified by a numbering system similar to the grade designation used in the ASTM specifications for corresponding base materials. These materials *shall* conform to the AWS classifications ER Ti-1, -2, -3, and -7 in the latest edition of AWS A5.16 [16]. This specification requires only chemical analysis for classification of the filler metal. To ensure a higher degree of quality control, conformance testing of each lot of material *shall* be performed in accordance with Schedule J of AWS A5.01 [17]. The lot classification for titanium filler materials *shall* be Class S2. The purchase order should clearly state that material classification is in accordance with this schedule and specification. It is also recommended that all filler materials be sealed in argon filled bags by the manufacturer prior to shipment. A supplement to the purchase specification will be necessary to ensure this degree of packaging.

The chemical composition requirements from A5.16 are provided in Table 4 for information. It is noted that AWS A5.16 permits ER Ti-1 filler material to be classified as ERTi-2 material. Generally, the filler material is selected to match the composition of the base metal. For example, ErTi-1/2 would be used with B862 or B363 Grade 2 base material. However, technical publication S9074-AR-GIB-010/278 [8] permits any of the filler materials to be used with any of the base materials if service conditions require a different grade of filler wire to give a desired combination of joint properties.

Table 4. Chemical composition requirements of filler materials.

Element	Composition, weight percent			
	ERTi-1	ERTi-2	ERTi-3	ERTi-7
Nitrogen, max	0.015	0.020	0.020	0.020
Carbon, max	0.03	0.03	0.03	0.03
Hydrogen, max	0.005	0.008	0.008	0.008
Iron, max	0.10	0.20	0.20	0.20
Oxygen, max	0.10	0.10	0.10-0.15	0.10
Palladium				0.12-0.25
Titanium	remainder	remainder	remainder	remainder
ASTM Base Material	Gr. 1	Gr. 2	Gr. 3	Gr. 7

4.3.2 Sizes

Titanium filler materials are available as either spooled wire or bare rod. Welding rod for manual welding is available in 1/16-, 5/64-, 3/32-, 1/8-, 5/32-, and 3/16-inch diameter with a straight length of 36-inches. Spooled wire is available in standard diameters of 0.020-, 0.030-, 0.035-, 0.045-, and 0.062-inch for automatic GTAW welding. Filler materials from 0.045- to 3/32-inch diameter are suitable for use up to a wall thickness of 0.180 inch.

5.0 WELDING AREA

The welding area is considered the physical area where welding is being done as well as the tools, equipment, staging and personnel within that area. An enclosed environment is necessary in which to weld titanium, whether in the shipyard or shipboard. To minimize the potential for interstitial contamination in shipboard welds due to drafts, winds and high humidity conditions all titanium components *shall* be designed to maximize the welding in a dedicated shipyard facility.

5.1 SHIPYARD

Although the use of a dedicated facility is recommended [8] for titanium fabrication, the shipyard/contractor may establish a temporary area for titanium welding using, for example, floor to ceiling curtains or tent-like enclosures. To ensure a controlled environment within the work area, the shipyard/contractor *shall* prepare a written facility procedure for NAVSEA review and approval that establishes work area requirements. Facility requirements include, as a minimum, the following controls:

- The work area *shall* be restricted from general traffic and protected from winds and drafts which might reduce the effectiveness of the inert gas shielding;
- The work area *shall* be isolated from dirt, smoke, residuals from grinding, welding and machining operations being done on other materials, and from other airborne contaminants;
- All equipment, including miscellaneous rigging and handling equipment, *shall* be cleaned to remove any accumulated dust and dirt before being brought into the work area. A regular clean-up schedule *shall* be established to prevent the accumulation of dirt, dust, and extraneous material. Clean up *shall* be accomplished using vacuum devices that exhaust outside of the work area.

A positive pressure air system should be operated continuously to preclude the entrance of dust and other airborne contaminants during facility work hours. The temperature and humidity in the work area should also be closely controlled. The work area should also be equipped with dehumidifiers to minimize atmospheric humidity. A relative humidity of 30% or less is recommended. Air conditioners are also recommended to further reduce the humidity by maintaining a temperature below 78° F during facility work hours. A checklist of required work

area cleanliness should be completed and filled out at the start of each shift. An example of a facility checklist is included in Appendix A.

5.2 SHIPBOARD

For shipboard welding, all titanium welds *shall* be designed for welder accessibility, inert gas shielding and environmental control. Whenever practical, the facility work area requirements developed by the shipyard should be applied for shipboard welding. For example, temporary enclosures, such as curtains or plastic tents, around the weld site are recommended to isolate the area from other welding, torch cutting, grinding or painting operations. Welding should also be performed inside flexible purge chambers to minimize the effect of drafts and high humidity conditions on inert gas shielding. Collapsible plastic chambers are made of transparent plastic as shown in Figure 2. This type of chamber is first collapsed and then flow-purged with argon or helium until the minimum dewpoint requirement (see Section 8) is achieved. Plastic chambers are available from a number of companies that supply specialized welding products to the commercial titanium piping industry. A selected list of manufacturers and suppliers related to titanium pipe welding is provided in Appendix B.

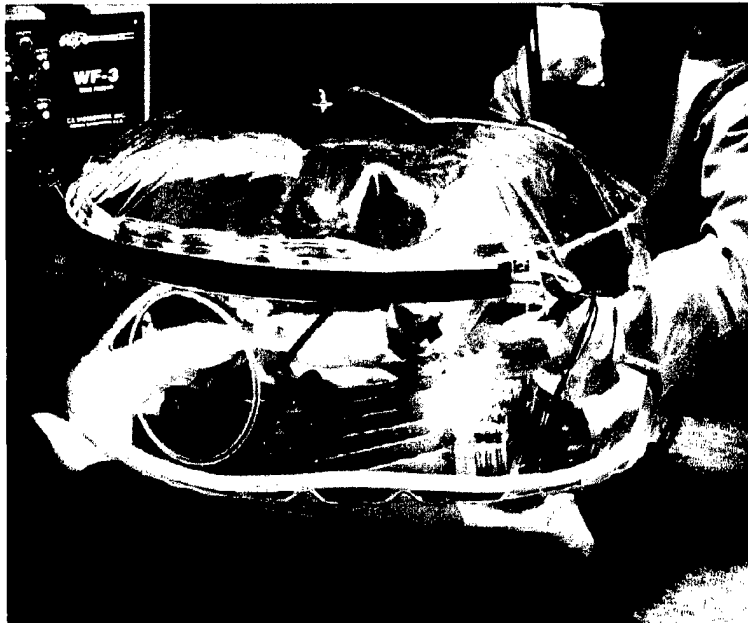


Figure 2. Collapsible plastic chamber for shipboard welding.

5.3 TOOLS

All tools that come in contact with the final surface of titanium piping components, such as carbide burs and stainless steel wire brushes *shall* be used only for titanium. All tools should be stored and maintained so they do not pick up grease, oil or other contaminants. Stainless steel wire brushes and wheels *shall* be free of contaminants and all tools should be degreased with an

approved solvent prior to initial use. Cleaning solvents *shall* be acetone, alcohol formula 23A, isopropyl alcohol, or other nonhalogenated solvent proven to have no adverse affect on titanium. Compressed air, either for pneumatic tools or blow cleaning of weld joints *shall not* be permitted in the welding area unless the facility procedure contains requirements that will preclude contamination of the base materials, filler materials and weld. Argon is recommended for blow-cleaning titanium weld joints.

5.4 PERSONNEL

All personnel that participate in the handling and welding of titanium should be required to wear clean, white coveralls and white cotton gloves. (Cotton gloves are not required during grinding operations, construction of shielding devices, equipment modification or repair and recording of written data). Clean, white cotton gloves or welding gloves should be used for handling titanium parts that have been cleaned for welding. Visitors and other personnel in the work area should not be permitted to handle titanium parts.

6.0 WELDING PROCESS

The gas tungsten arc welding (GTAW) process is used in titanium pipe welding because of its precise control of the welding parameters and excellent control of root pass weld penetration. In addition, the process produces high quality welds, generally free of defects, it is free of the spatter which may occur with gas metal arc welding, and can be used with or without filler metal depending on the specific application.

The three process variations of GTAW are manual, semi-automatic and automatic welding. Manual welding refers to the process variation in which the welder manipulates the welding torch and filler wire by hand. If a motorized wire feeder is attached to the torch, the process is classified as semi-automatic welding. Automatic gas tungsten arc welding systems incorporate arc voltage controls, arc oscillators and wire feed systems. The most common application of automatic welding is associated with orbital pipe welding systems.

Orbital welding provides a means to ensure high productivity and optimum weld quality. It is expected that this process variation will be used in the shipyard to fabricate the majority of titanium piping assemblies. These systems are portable and can also be used shipboard for joining the subassemblies. Both manual and semi-automatic welding can also be used on-board ship for repair welding of titanium pipe or welding in areas of limited accessibility.

7.0 WELDING EQUIPMENT

7.1 POWER SUPPLY

The power supply provides the current and voltage for welding. A constant current power source, connected d. c. electrode negative, is always used for GTAW of titanium. These power sources have either a drooping (transformer-rectifier) or nearly constant (inverter) current output characteristic. The drooping characteristic of the transformer-rectifier is advantageous for manual GTAW when a foot pedal is not available at the welding site, since the welder can change the current level slightly by changing the arc length.

Inverters are the preferred power source for automatic GTAW of titanium pipe because the current can be controlled more precisely. These machines also have a faster response time due to the use of power transistors, and therefore a more stable welding arc than an SCR controlled transformer-rectifier. Either type of power supply should include a remote controlled contactor or foot operated contactor control, to extinguish the arc without pulling the torch away from the joint, thereby maintaining inert gas shielding of the weld.

High frequency power or other non-contact method should be used to initiate the arc. Scratch starting with tungsten electrodes is a common source of tungsten inclusions in the weld and should never be used for arc initiation. Shielding gas timers for torch gas preflow and postflow are also recommended.

7.2 WELDING TORCH

The welding torch holds the tungsten electrode and also serves as a conduit for shielding gas to protect the electrode, welding arc and molten weld pool. Welding torches are of two types; manual and automatic, and rated in accordance with the maximum current that can be used at 100% duty cycle without overheating. Gas and/or water-cooled manual torches are used for both manual and semi-automatic GTAW of titanium. These torches are available with both rigid and flexible necks and adjustable head angles for welding in areas of limited accessibility. Water-cooled torches are used for automatic GTAW. Trailing shields, which attach to titanium welding torches, are discussed in Section 9.3 of this report.

7.3 TUNGSTEN ELECTRODE

7.3.1 Classification and Sizes

Tungsten electrodes are non-consumable and serve to conduct the current to the welding arc. Electrodes are available in pure tungsten or alloyed with oxides of cerium, lanthanum, thorium, or zirconium for improved arc starting, longer life and higher operating currents. Tungsten electrodes are classified on the basis of their chemical compositions, as shown in Table 5 from ANSI-AWS A5.12 [18]. Each type has a color code and individual electrodes are marked by the manufacturer, usually with a band or dot of the appropriate color, on one end of the electrode.

Table 5. Tungsten and tungsten alloy electrodes.

Classification*	Color	Alloying Element	Alloying oxide	Nominal Weight of Alloying Oxide, %
EWP	Green	-	-	-
EWCe-2	Orange	Cerium	CeO ₂	2
EWLa-1	Black	Lanthanum	La ₂ O ₃	1
EWLa-1.5	Gold	Lanthanum	La ₂ O ₃	1.5
EWLa-2	Blue	Lanthanum	La ₂ O ₃	2
EWTh-1	Yellow	Thorium	ThO ₂	1
EWTh-2	Red	Thorium	ThO ₂	2
EWZr-1	Brown	Zirconium	ZrO ₂	0.25
* In the AWS classification system, E stands for electrode, W stands for the chemical symbol for tungsten and the final letters indicate the alloying element. The number specifies the nominal weight percent of the alloy addition.				

Thoriated tungsten electrodes were developed specifically for direct current, electrode negative (DCEN) welding applications and the 2% thoriated electrode, color-coded red, is recommended for GTAW of titanium piping systems. However, thorium is a low-level radioactive material. The grindings may be considered hazardous waste and disposal may be subject to environmental regulations in some states. Both cerium and lanthanum are non-radioactive. The 2% lanthanated electrode has similar operating characteristics as the 2% thoriated electrode and can be used as non-radioactive substitute.

Tungsten electrodes are available in a variety of standard diameters from 0.010- to 0.25-inch diameter and standard lengths of 3, 6, 7, 12, 18 and 24 inches. Shorter electrodes (1/4 to 2 inches) for orbital pipe welding systems are available from the equipment manufacturers or other suppliers. Upon delivery, tungsten electrodes should always be handled carefully and stored in their original package until used.

7.3.2 Electrode Tip Shape

Tungsten electrodes are supplied from the manufacturer with either a pre-cut length and pre-ground tip configuration or with a blunt end that requires some type of tip preparation. For thoriated, ceriated and lanthanated electrodes used in titanium welding, the end of the electrode is generally ground to a conical shape with a specific included angle, and truncated end as shown in Figure 3. The truncated end is recommended to reduce tip erosion. The length of the tapered region is a function of the included angle. Grinding the end of the electrode to about a 30 degree included angle, will give a taper length equal to about 2 times the nominal diameter of the electrode.

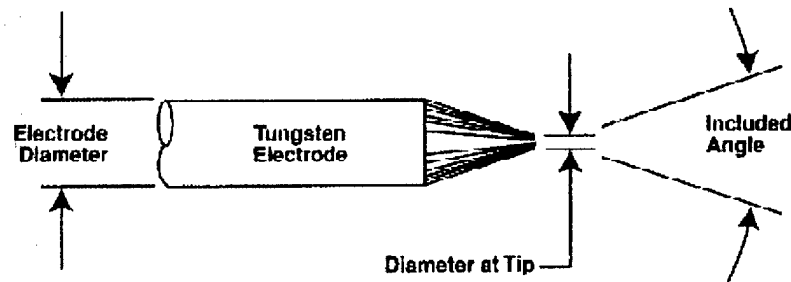


Figure 3. Tungsten electrode tip shape.

The electrode tip geometry is an important process variable in GTAW, particularly in thin wall pipe welding, because of its effect on weld bead shape and size. In general, as the included angle increases, the weld bead penetration increases and the width of the weld bead decreases. The change in bead shape with tip geometry is due to a change in the shape of the arc plasma as shown in Figure 4. A sharply tapered tip (20° included angle) produces a diffuse plasma, which radiates the arc heat over a large surface area. The more focused arc plasma emanating from the blunt tip (90° included angle) concentrates the arc heat in a smaller region, increasing weld penetration and decreasing weld width.

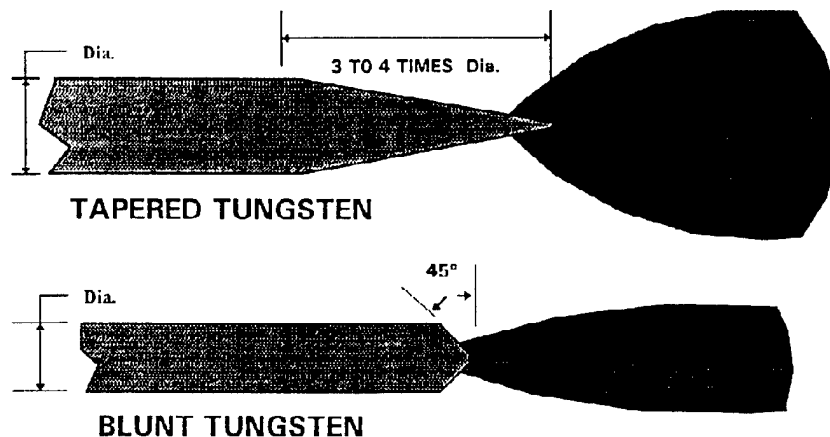


Figure 4. Effect of electrode tip shape on arc plasma.

The included angle and tip truncation diameter also determines the operational position of the electrode in orbital pipe welding systems equipped with a voltage feedback control loop. As the included angle and tip truncation diameter decrease, the electrode operates progressively closer to the weld pool surface for the same set of welding parameters. From an operational standpoint, this means that sharply tapered electrodes will be more susceptible to contamination and short-circuiting.

The selection of an electrode size and tip configuration is dependent upon the anticipated

operating current. Too large a current will split or melt the electrode promoting tungsten inclusions in the weld, while too small a current will result in electrode erosion and arc instability. Table 6 is a guide for electrode tip preparation for a range of electrode sizes and recommended current ranges. The selection of a specific size and tip shape should be performed during welding procedure development. To ensure uniform penetration in thin-walled titanium pipe, particularly in automatic welding, it is important that the same electrode geometry be maintained through production welding of the piping assemblies.

Table 6. Electrode size, tip shape and current ranges.

Electrode Diameter inch	Diameter at Tip inch	Included Angle degrees	Current Range Amperes	Pulsed Current Range Amperes
0.040	0.005	12	2-15	2-25
0.040	0.010	20	5-30	5-60
0.060 (1/16)	0.020	25	8-50	8-100
0.060 (1/16)	0.030	30	10-70	10-140
0.093 (3/32)	0.030	35	12-90	12-180
0.093 (3/32)	0.045	45	15-150	15-250
0.125 (1/8)	0.045	60	20-200	20-300
0.125 (1/8)	0.060	90	25-250	25-350
*All values are based on the use of argon as the shielding gas. Other current values may be used depending on the type of power source, electrode extension and shielding gas.				

To ensure a constant tip shape, it is recommended that tungsten electrode grinders be used for preparation of the electrode tips. If conventional grinding wheels are used, the electrode should be ground along the length (longitudinally) of the tungsten. The grinding wheel should be dedicated to titanium use only to avoid potential contamination of the electrode with foreign matter. Care should be taken during sharpening operations not to inhale the tungsten metal dust. The dust generated by grinding may be considered a health hazard and all metal grinding machines should be equipped with dust extractor systems that will collect the grinding debris and dust, filter it and properly store it.

8.0 ORBITAL PIPE WELDING SYSTEMS

Orbital GTAW systems are designed for welding pipe in a fixed position, whether horizontal, vertical or at an angle. The main advantage of orbital welding is the ability to produce high quality welds on a consistent basis at a lower operator skill level. If the workflow is arranged to allow welding of a number of similarly sized pipes in uninterrupted succession, the productivity is significantly increased over manual welding.

Orbital welding systems incorporate all of the equipment components discussed in Section 6.0 above. An inverter is used as the power source and also controls the various functions of the welding head. The power output ranges from 100 amperes for lightweight portable units to 300 amperes for units designed for multi-pass welding. The welding head component contains a

water-cooled torch, tungsten electrode, electronic arc gap (arc length) control device, cold wire feed system and torch oscillation controls.

Welding heads are of two types, enclosed and open design. Enclosed heads clamp on the pipe and remain stationary while the torch and other control mechanisms (arc voltage control and electronic torch oscillation) mount on a rotating module. The filler wire feeder may be mounted on the rotary portion of the head or may be floor mounted with a conduit connected to the rotating module. Floor mounted wire feeders allow the use of larger wire spools but are not recommended due to a potential sacrifice in wire feeding accuracy. An inert gas atmosphere is maintained inside the head to protect the liquid puddle and solidified weld from atmospheric contamination. Backside shielding is still required to protect of the root of the weld. Enclosed heads clamp on pipes within a specified outside diameter range, with each model welding a finite range of pipe sizes.

The open head attaches to the pipe using a metal band or guide ring fabricated to match the size of the pipe, Figure 5. Unlike the enclosed head, the entire head mechanism (torch rotation, filler wire feed, arc voltage control and torch oscillation) rotates around the pipe. Open head systems are recommended for titanium pipe welding for several reasons. Each model can cover more pipe sizes as compared with the enclosed head design. The radial clearance remains constant on all pipe sizes and the head design permits water cooling of the body, which allows it to be used on alloys requiring preheat. Shielding gas supplied through the welding torch protects the liquid puddle from atmospheric contamination. However, a trailing shield must be fabricated and adapted to the torch and pipe diameter to protect the solidified weld, along with provisions for backside shielding. One alternative to fabrication of a trailing shield is to construct a rotatable purge containment around the welding head to protect the solidified weld. Purge containments and other shielding techniques are discussed in the next section.

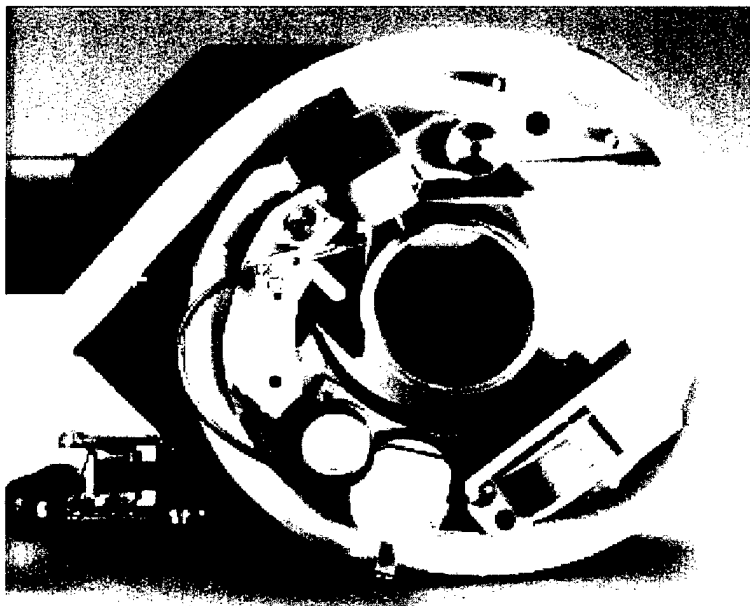


Figure 5. Open head orbital pipe welding system.

9.0 GAS SHIELDING

Only the inert gases argon, helium or argon/helium mixtures *shall* be used in titanium welding to protect the weld, heat-affected zone (HAZ) and adjacent base material from interstitial contamination by atmospheric elements at welding temperatures. Gas shielding *shall* be maintained until the completion of each welding pass. The surface color of the as-deposited weld is an indicator of shielding effectiveness. A bright and lustrous silver color can be taken as an indication of proper shielding. A change in surface color from silver to light and dark straw, purple, dark blue, light blue, dull gray and powder white represent progressively worse gas shielding performance. Separate gas supplies and flow controls are needed for:

- Primary shielding of the of the molten weld pool;
- Secondary shielding of the cooling weld deposit, HAZ and adjacent base material;
- Back shielding of the backside of the weld, associated HAZ and base material.

For all types of shielding, it is very important that the shielding gas be delivered in an even diffuse blanket. This prevents the formation of high velocity, turbulent streams, which will aspirate air into the shielding gas. All shielding devices discussed in the following sections should be examined to ensure proper operation and prevent deterioration of any components, which might cause weld contamination.

9.1 GAS PROPERTIES

Gas selection is driven by the physical properties of the shielding gases, Table 7, which have a major effect on arc characteristics, heat input and overall process performance. Argon is the most commonly used shielding gas for several reasons. It has better arc starting characteristics because of a lower ionization potential,* which makes it easier to initiate the arc and maintain it in a smooth, stable fashion. Argon also provides more efficient coverage of the weld zone because of its higher density. Argon is approximately 1.4 times as heavy as air and ten times as heavy as helium. Argon, after leaving the torch nozzle, forms a blanket over the molten pool, whereas helium tends to rise in somewhat turbulent fashion. (To produce equivalent shielding, the flow of helium must be two to two and one half times that of argon. The same general relationship is true for mixtures of argon and helium.) Argon is also more readily available and less costly than helium.

* Ionization potential is the energy, expressed in electron volts (Ev), necessary to remove an electron from an atom making it an ion or an electrically charged gas atom. The energy required to remove the first electron in argon is significantly less than that needed for helium. At these energy levels, ionization of the gas begins in the arc gap, which creates the free electrons necessary for current flow across the gap, forming the arc plasma.

Table 7. Physical properties of shielding gases.

Gas	Molecular Weight	Density lb/cu. ft.	Ionization Potential Ev	Thermal Conductivity 10^{-3} Btu/hr-ft-°F
Argon	39.95	0.114	15.7	9.69
Helium	4.00	0.0111	24.5	85.87

The arc voltage is directly influenced by the ionization potential of the shielding gas. For equivalent arc lengths and welding currents, the voltage obtained with 100% helium is higher than it is with 100% argon, Figure 6. Because heat in the arc is roughly equivalent to the product of the voltage and amperage, the heat energy liberated in helium is about twice that in argon, Figure 7. This is why helium is commonly referred to as the “hotter” of the two gases.

The penetration profiles are a function of the gas thermal properties. Argon, which has a lower thermal conductivity, produces a welding arc with two zones: a narrow hot core and a considerably cooler outer zone. As a result, the penetration profile in titanium exhibits a narrow “finger” at the root and a wider top as shown in Figure 7. Helium has a higher thermal conductivity which conducts more of the heat outward from the center core, resulting in a wider, hotter arc. This type of heat distribution gives a more even heat input to the work-piece surface and produces an overall wider profile throughout the fusion zone. Mixtures of argon and helium (75% argon and 25% helium) combine the positive benefits of each gas, and may be of benefit in certain pipe welding applications.

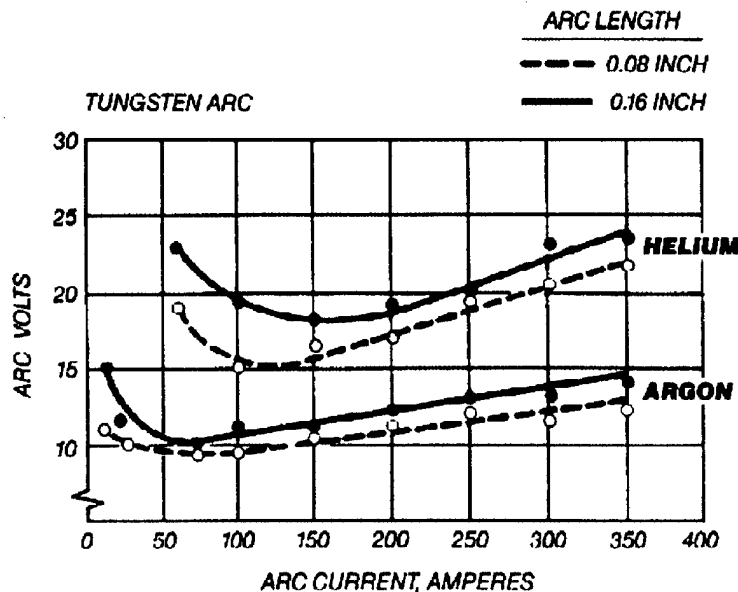


Figure 6. Arc voltage as a function of the shielding gas.

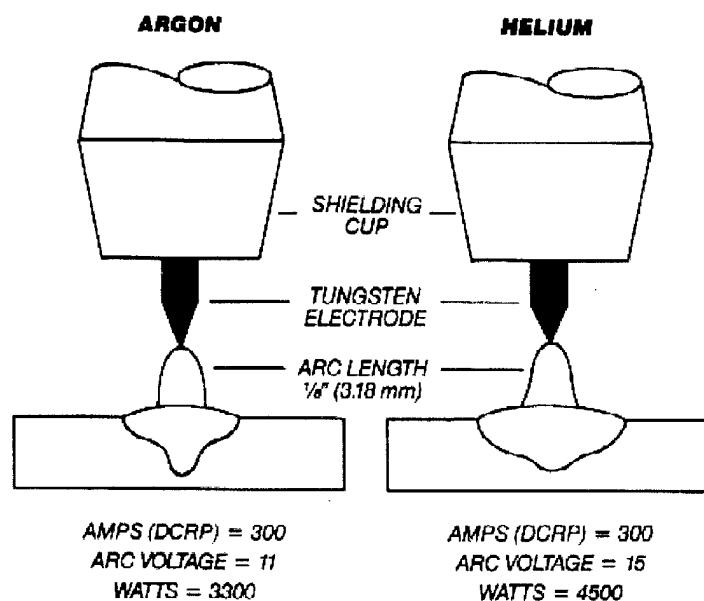


Figure 7. Heat energy at constant arc length.

9.2 GAS PURITY

The low tolerance of titanium to interstitial contamination from atmospheric elements also extends to gas impurities and moisture in the shielding gas. All inert gases used in titanium welding *shall* have a purity of at least 99.995 percent and a dewpoint of -60°F or less at the workpiece or purge exit. Only AWS certified shielding grade gases conforming to the requirements of ANSI/AWS A5.32 [20] are recommended for titanium welding. The purity and dewpoint requirements from this specification are provided in Table 8 for information.

Table 8. Shielding gas purity and dewpoint.

Gas	AWS Class.	Product State	Minimum Purity %	Maximum Moisture ppm	Dewpoint at Maximum Moisture Content ° F
Argon	SG-A	Gas	99.997	10.5	-76
		Liquid	99.997	10.5	-76
Helium	SG-H	Gas	99.995	15	-71
		Liquid	99.995	15	-71

9.3 GAS DISTRIBUTION

Shielding gases are supplied in cylinders or as a liquid in insulated tanks. Liquid gas is vaporized and piped to points within the fabrication facility through a manifold system. All exterior gas lines should be stainless steel except where flexibility or electrical insulation is

required. All manifolds, valves, regulators, flowmeters, fittings, hoses, tubing, torches and other associated equipment should be clean, leak-free and free of moisture.

Gas hoses for titanium welding *shall* be new and only used for inert gases. These hoses should be nonporous, flexible and made only of welding quality Tygon or vinyl plastic. A comparison of moisture permeation in three types of gas hoses commonly used in titanium welding is shown in Figure 8. Both FEP lined Tygon and FEP tubing exhibit superior resistance to moisture absorption as compared with PVC tubing. FEP lined Tygon is more flexible as compared with FEP tubing and is recommended for use in titanium pipe welding. Rubber hoses absorb excessive quantities of moisture and should never be used in any titanium welding operation. Periodic inspection of the gas delivery system for fitting leaks, hose cracks and pinholes is recommended. Joints and hoses can be checked for leaks using a weak (typically 0.5 percent) solution of a detergent in water or a leak-detecting solution from a gas supply company.

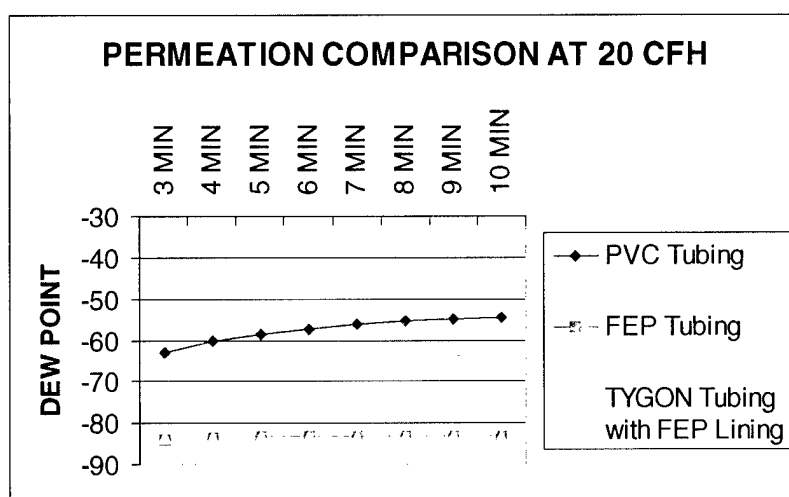


Figure 8. Moisture permeation in gas tubing.

9.4 PRIMARY SHIELDING

The torch shielding gas provides primary shielding of the liquid weld pool. The torch gas is directed to the weld zone by gas nozzles or cups, which fit onto the head of the torch. Gas nozzles are made of various heat resistant materials. Alumina nozzles are inexpensive and are generally recommended for the low to intermediate current levels used in titanium pipe welding. The more expensive water-cooled metal nozzles are generally selected for automatic welding applications where the welding current exceeds 250 amperes. Fused quartz nozzles are transparent and are recommended for manual and semi-automatic welding of titanium, because they allow better vision of the arc and tungsten electrode.

Gas nozzles are supplied in different sizes, shapes and lengths. Size selection depends on tungsten electrode size, type of weld joint, weld area to be shielded and access to the weld joint. Larger nozzles are recommended for welding titanium than those used for welding other

materials. With a 1/32-inch diameter electrode, a 9/16-inch ID nozzle is used, and with a 1/16-inch diameter electrode, a 3/4-inch ID nozzle is used. Larger 1 1/8-inch clear, pyrex nozzles are now also available for manual GTAW torches, Figure 9. This type of nozzle and associated gas lens may allow an electrode extension up to 10 times the diameter of the tungsten, which can be of benefit for fillet welding or welding in areas of limited accessibility aboard ship.



Figure 9. Manual GTAW torch equipped with large diameter gas lens and nozzle.

A timer controlled pre-flow of torch shielding gas is recommended to remove any moisture which may have condensed on the inside of the torch owing to changes in the surrounding temperature. Gas pre-flow also helps minimize potential contamination at the start of welding. The pre-flow interval may range from a few seconds in an environmentally controlled area to 30 or more seconds in high humidity conditions. A timer controlled post-flow of torch shielding gas is recommended for a minimum of 30 seconds after the arc has extinguished to protect the just solidified weld and the tungsten electrode from contamination.

Pure argon is recommended as the torch shielding gas because of better arc stability. A torch gas mixture of 75%Ar-25%He can be used if a hotter arc and increased penetration is desired. Helium by itself should never be used for torch shielding due to its poor arc starting characteristics. Only the minimum amount of torch shielding gas that provides effective shielding should be used. Excessive flows will entrain air into the welding arc, resulting in contamination of the weld deposit. While the manufacturer's recommended gas flow rates to the torch should be used, argon flow rates in the vicinity of 20 cfh have proven satisfactory in titanium pipe welding practice.

9.5 SECONDARY SHIELDING

Trailing shields attach to the tungsten holder on manual or automatic torches and are used to provide secondary shielding of the solidified weld and adjacent heat-affected-zone. Although trailing shield design is a somewhat individualistic art, the following recommendations can be made:

- The shield body should be constructed of copper, aluminum or stainless steel. Copper

tubing should be used to deliver the gas. Degreased stainless steel wool, porous bronze or other type of diffuser can be used as the diffusing medium. The possible need for water-cooling should also be considered, particularly for large shields.

- The welding torch should go through the shield body so that the shield extends about 1-inch ahead of the torch to ensure that some of the trailing shield gas is distributed ahead of and around the weld puddle.
- Shields are most effective when the shape of the shield conforms to the general contour of the pipe, and when the bottom edges of the shield are held to within 1/4-inch of the weld surface.
- The shielding gas should be directed toward the top of the shield body, and then deflected downward through the diffusing medium (i.e., stainless steel wool or porous bronze) to prevent streaming. A copper or similar screening material of sufficiently fine mesh can be used to close the shield bottom.

Trailing shields for titanium pipe welding are generally custom-made to fit a particularly welding application. A trailing shield fabricated for manual GTAW of 4-inch diameter, schedule 10S pipe is illustrated in Figure 10. This shield was constructed using aluminum for the body, a brass screen to hold the stainless steel wool-diffusing medium in place and tygon tubing to deliver the shielding gas. A trailing shield for automatic GTAW of 4-inch diameter schedule 10S pipe is shown in Figure 11. This shield was constructed using aluminum for the body and mesh metal as the diffusing medium. Variations of these devices can be adapted for different fabrication conditions.



Figure 10. Trailing shield constructed for manual GTAW of titanium pipe.

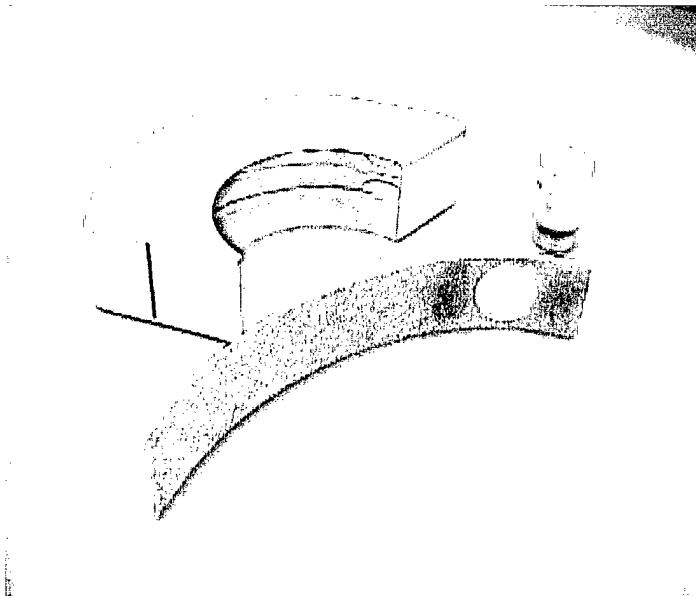
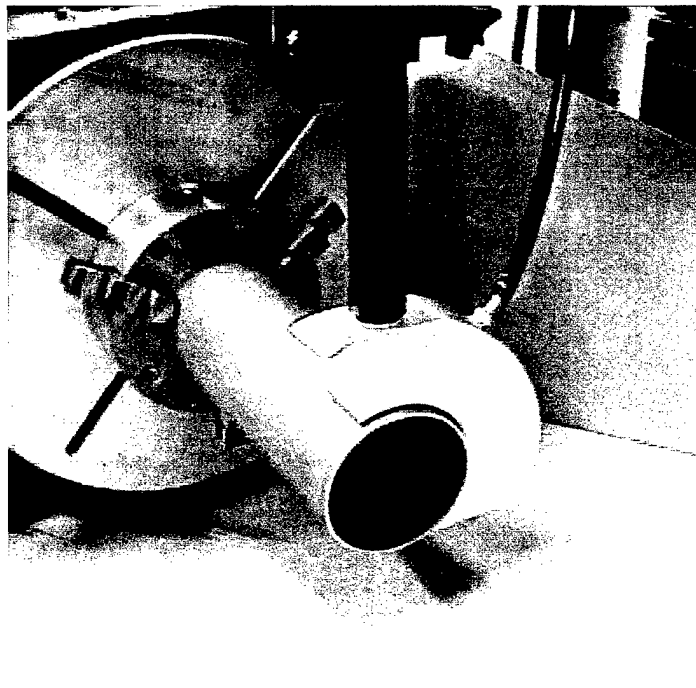


Figure 11. Trailing shield constructed for automatic GTAW of titanium pipe.

Commercially available trailing shields can also be used for secondary shielding of titanium pipe welds, Figure 12. These shields can be supplied by the manufacturer (see Appendix B) to fit any make of GTAW torch for both manual and automatic welding of titanium pipe. Pre-fabricated shields are available with variable radii to match each pipe diameter, and can be contoured for either outside or inside welding.

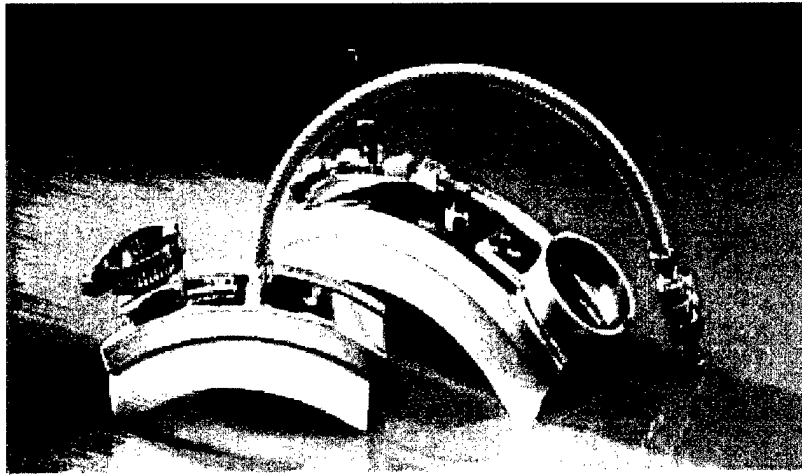


Figure 12. Pre-fabricated trailing shields for titanium pipe welding.

The width and length of the trailing shield is a function of the welding speed and must be determined for each particular joint design during welding procedure development. If the trailing shield is too short, interstitial contamination of the solidified weld will occur until the temperature has cooled below 800° F. This condition occurs most frequently on small diameter pipe, when welding 360 degrees without stopping. With a conventional trailing shield, a stop and start technique can be used to minimize heat build-up.

Other methods are also available for situations where a conventional trailing shield is too short. One of these is the use of a trailing shield that provides inert gas coverage of the entire circumference of the piping joint. Figure 13 illustrates a hinged trailing shield that was constructed for automatic GTAW of 2-inch diameter schedule 10 pipe. Purge containment bags can also be constructed around the pipe joint. A rotatable purge containment that was constructed of heat resistant glass tape for manual GTAW of 4-inch diameter schedule 10 pipe is shown in Figure 14.

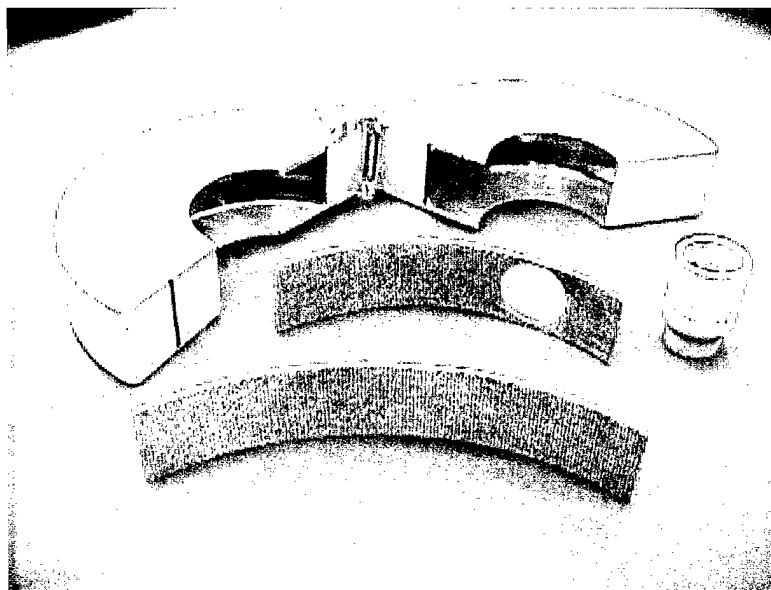
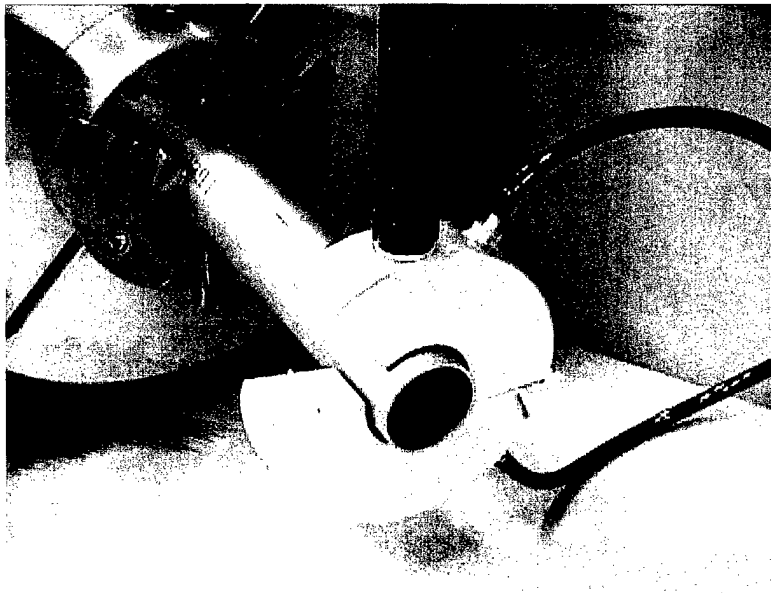


Figure 13. Hinged trailing shield for automatic GTAW of small diameter pipe.

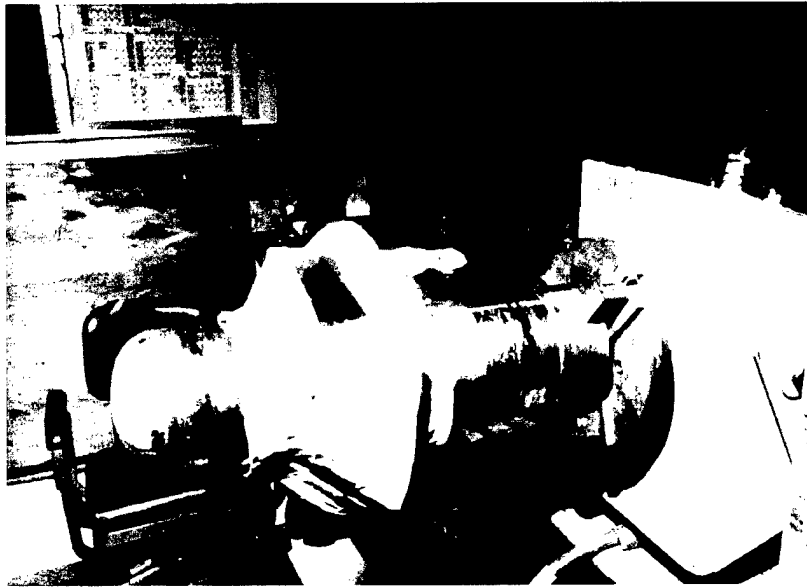


Figure 14. Rotatable purge containment for manual GTAW of titanium pipe.

9.6 BACK SHIELDING

Backside shielding provides inert gas coverage to the root side of welds, their heat-affected zones and adjacent base material. The backside of titanium *shall* be shielded with inert gas unless the backside temperature of the weld remains below 500° F. For titanium piping materials, the backside temperature will always exceed 500° F and require backside shielding. For thicker titanium materials (> 1-inch) backside shielding may not be required. To eliminate backside shielding, the shipyard/contractor *shall* measure the temperature of the backside surface during welding with a pyrometer. If the backside is inaccessible, a mockup of the weldment heat sink simulating worst case production conditions *shall* be welded by the shipyard/contractor. Temperature measurements from the mockup *shall* be obtained to demonstrate that the backside temperature will remain below 500° F during all production welding. A description of the mock-up and test results *shall* be maintained with the procedure qualification record and submitted to NAVSEA or its authorized representative for review and approval.

Argon gas is recommended for backside shielding, although helium is sometimes used for trailing or backup shielding when the weld is located above the shielding device. For fabrication of piping subassemblies in the shipyard facility, the gas can be confined within the pipe by sealing both ends with plastic disks or caps and masking tape. Holes are cut in each disk or cap to serve as purge gas entrance and exit holes. On large diameter pipe or long piping runs aboard ship it may be too expensive to fully purge these sections. One approach is the use of commercially available dams to contain the backside purge gas. These dams can be simple rubber or plastic disks with one disk connected to a gas inlet line and the other disk vented to prevent built-up of gas pressure, Figure 15. At least one end of the pipe assembly must be left open for removal of the disks after welding.

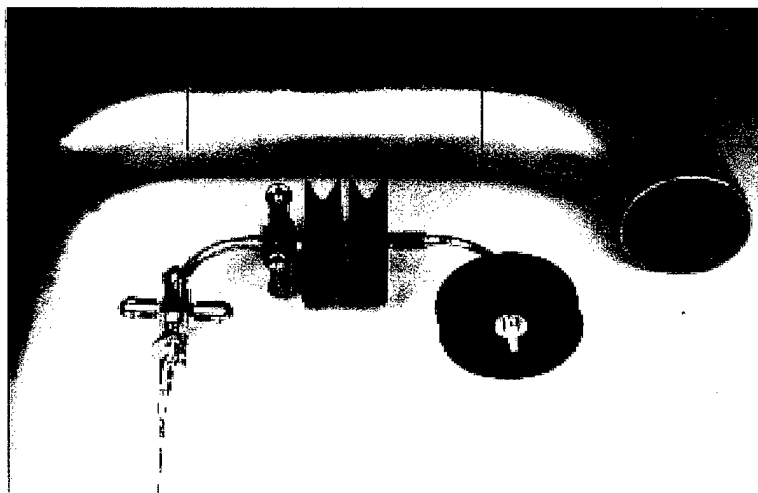


Figure 15. Rubber disk system for backside purge containment.

When the use of dams is impractical, water dissolvable plastic film can be used to contain the purge gas. These commercially available kits are supplied with a roll of plastic film, adhesive and application instructions, Figure 16. In practice, an appropriately sized piece of plastic is attached with adhesive to the ID of the pipe on each side of the joint. For large diameter pipe and short piping runs, gas inlet and outlet holes can be cut in the plastic. For small diameter pipe and long piping runs where the plastic film is not accessible from the end of the pipe system, small diameter holes must be drilled on each side of the joint to provide purge gas inlet and outlet holes. After the joint is completed, the plastic seal can be dissolved with water flushed through the pipe. The manufacturer's instructions should be carefully followed to ensure that the dam material is far enough away from the joint to prevent overheating or burning. Typically a distance of 12-inches is adequate.

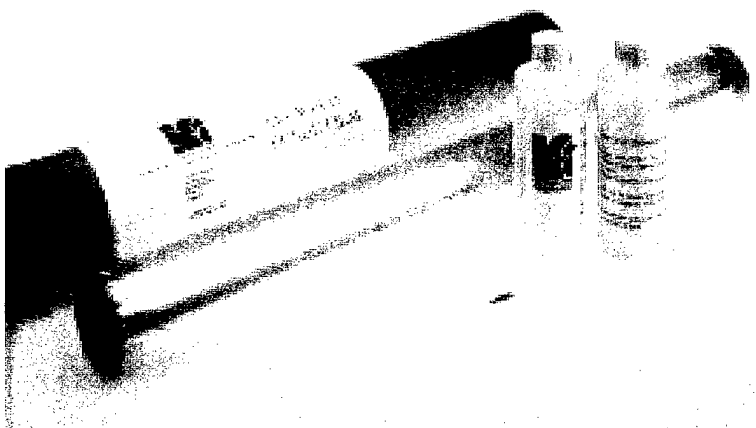


Figure 16. Water soluble plastic film kit for backside purge containment.

Regardless of the type of purge containment device, it is very important that the gas purge inlet is located at the lowest point of the piping assembly, and the gas purge outlet is located at the highest point, Figure 17. Since air is lighter than argon, the argon purge gas will force the air inside the pipe upward and out of the piping system. In addition to sealing branch connections, all branch pipes should be vented with a small diameter ($\sim 3/32$ -inch) hole to minimize the entrapment of air. To prevent the purging gas from escaping through the weld groove, a layer of plastic should be wrapped around the outside of each joint in the purged piping system. Tape may leave residue on the joint surfaces and is not recommended for sealing any groove.

Purging a titanium piping system is similar to the techniques described in ANSI/AWS D10.11 [19] for steel piping. Pre-purging is a two-stage operation. In the first stage prior to welding, the purge gas is used to displace the air in the pipe at relatively high flow rates. This high flow rate is maintained until the inert gas inside the pipe reaches an acceptable dewpoint level as described in Section 9.6. Prior to arc initiation, the purge gas flow rate is reduced so that the purge maintains a slight positive pressure on the inside of the pipe.

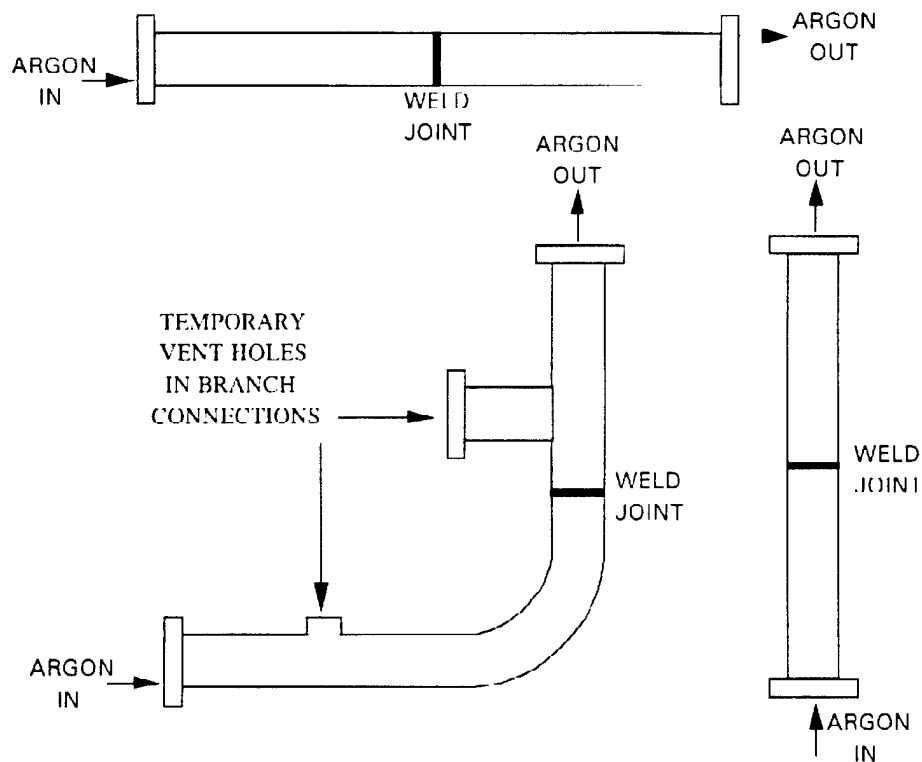


Figure 17. Pre-weld purge inlet and outlet locations.

The time required for the first stage of purging depends on the minimum acceptable dewpoint level of the purge gas, the volume of the pipe being purged and purge gas flow rate. A guide for pre-purge times for various titanium pipe diameters is provided in Table 9. The purge times were calculated to produce a 20-volume change using a purge gas flow rate of 50 cfh.* The pre-purge time for any length of pipe can be calculated by multiplying the value from the table by the length of the pipe. At the completion of the pre-weld purge time, all vents in branch connections should be closed. The purge gas flow rate should be reduced to approximately 20 cfh to eliminate excessive internal pressure on the inside of the pipe, which can cause root surface concavity or holes through the root bead. Prior to arc initiation, the dewpoint of the purge gas should be checked at the purge gas outlet hole. It is recommended that the dewpoint of the backside purge gas be checked and recorded for each welding pass or weld repair. Dewpoint measurement requirements are discussed in the following section.

Table 9. Pre-purging times for titanium pipe.

Nominal Pipe Size	Pre-Purge Time per 1-foot of Titanium Pipe
Under 3	1 min
4	2 min
6	2 min 45 sec
8	8 min 15 sec
10	13 min
12	18 min 45 sec
14	25 min 15 sec
16	31 min 45 sec
Note: Values are based on a gas flow rate of 50 cfh. Other purge gas flow rates will require different purging times that may be calculated using the guidelines provided in ANSI/AWS D10.11 [19].	

9.7 DEW POINT MEASUREMENTS

While the AWS dewpoint requirements previously reported in Table 9 are below the minimum required dewpoint for titanium shielding gases, there is always the possibility of the gas being contaminated either as delivered or somewhere between the supply and the end-use point. To ensure gas quality at the end-use point, a dewpoint check of the gas system *shall* be performed at the workpiece or purge exit. The dewpoint of the torch gas, trailing shield gas and purge gas *shall* be measured at the beginning of each worker shift or whenever the gas flow is interrupted, i.e., during a change in gas cylinders or replacement of a gas hose. The dewpoint *shall* also be measured for each weld or weld repair that is not inspected on the backside of the joint due to inaccessibility. As noted previously, the dewpoint of the shielding and purge gases *shall* be -60° F

* The purging times in Figure 2 of ANSI/AWS D10.11 [19] produce a 5 to 6 volume change and are not recommended for titanium. A 20 volume change is recommended for titanium pipe welding to obtain the necessary level of purity to meet dewpoint requirements.

or less and welding is prohibited until the required dewpoint is achieved at the measurement site. Due to the significant labor costs associated with titanium weld repair from atmospheric contamination, it is recommended that dewpoint measurements be made for each welding pass and weld repair regardless of visual accessibility. During non-production times, a continuous, low flow purge of 1-2cfh is recommended to eliminate air re-entry into the gas supply system

The puddle test described in ANSI/AWS D10.6 [21] may also be employed as a quantitative check of the torch and purge gas. In this test, a cleaned 1/16-inch thick titanium sheet is placed over the joint after purging the pipe. A spot weld is deposited on the surface of the sheet. Both sides of the sheet should be silver in color. If the backside shows discoloration, the purge is ineffective. Similarly, the effectiveness of the trailing shield gas can be checked by producing a short length of weld on titanium sheet of a configuration similar to the production joint.

10.0 WELD JOINT DESIGN

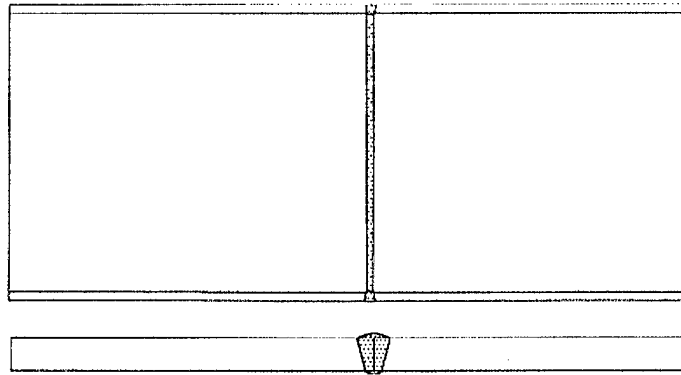
Weld joint designs for titanium piping are similar to those for other piping materials. Approved joint designs are provided in Table VII of technical publication S9074-AR-GIB-010/278 [8] for each piping class. Piping system joint design details are provided in MIL-STD-22 [22], and are designated by the letter "P". Representative joint types for titanium seawater piping include the P-1 square groove and the P-80 bell end joint designs, as shown in Figure 18.

The P-1 joint with a machined square groove, no gap and minimal mismatch can be welded in a single pass without filler material up to about 0.125-inch wall thickness. P-1 joints prepared by sawing can result in fit-up gaps and mismatch that may require two passes to achieve satisfactory weld contour, including a root pass without filler and a capping pass with filler.

At pipe sizes above 0.125-inch, undercutting may present a problem in autogeneous welds. At 0.125-inch wall thickness, the P-1 square groove may be designed to have a slight root opening for welding with filler wire. Alternatively, a P-6 U-groove with a land can be used for initial welding of the root pass without filler. The remainder of the weld can be completed in one or more passes.

Where permitted, the P-15 socket and P-80 bell end joint can provide significant reductions in joint preparation time and misalignment problems encountered in butt-welded pipe to pipe or pipe to flange joints. Figure 19 illustrates the attachment of socket and welding neck flanges to a 12-inch diameter, schedule 10S pipe using P-1 butt and P-15 fillet welds, respectively.

P-1 Square Butt Joint



P-80 Bell End Joint

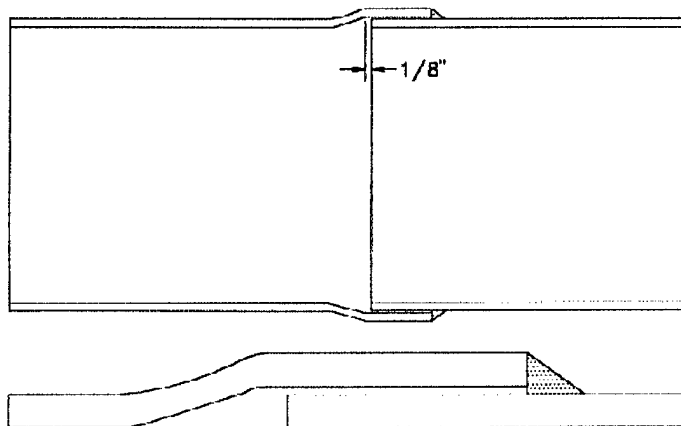


Figure 18. Weld joint designs for titanium piping.

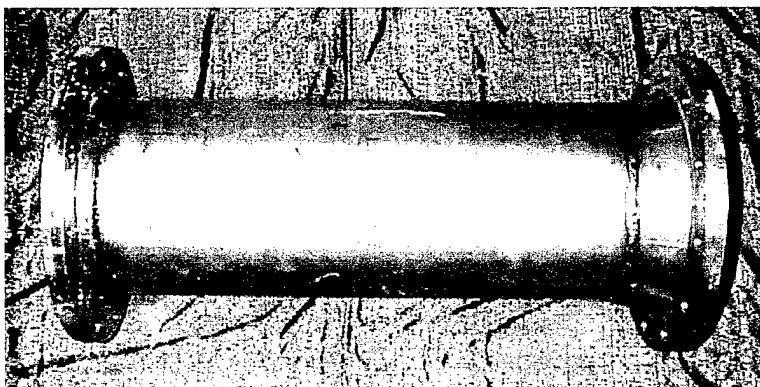


Figure 19. Fillet and butt welded flanges.

11.0 JOINT PREPARATION

11.1 THERMAL CUTTING

In some circumstances it may be necessary to perform oxy-fuel or plasma-arc cutting operations, such as when there is no access for other cutting operations during the installation process aboard ship. When using oxy-fuel or plasma-arc cutting, local exhaust ventilation should be present and supply a minimum air flow to maintain a capture velocity of 100 linear feet per minute in the cutting zone. When local exhaust ventilation is not feasible or inadequate, respirators should be worn. Cartridge type respirators will protect the wearer against metal fumes, but not gases such as carbon monoxide and nitrogen dioxide. It is noted that the carbon arc process should never be used for cutting or metal removal of titanium.

Thermal cut surfaces *shall* be conditioned to remove the contaminated surface layer prior to welding. A minimum of 1/8-inch of material beyond the kerf *shall* be removed by sawing, machining or carbide burring. If steel tools are used, the joint surfaces *shall* be dressed with carbide burrs or files to remove all surface markings from the cutting operation. The conditioned thermal cut surface *shall* be visually inspected at 5X magnification to ensure the absence of cracks. Finally, portable hardness testing *shall* be performed at 6-inch intervals on the conditioned surface. The hardness of the conditioned cut surface cannot be more than 3 points Rockwell C* higher than that of the base material. The hardness of the base material *shall* be determined by calculating the average of 10 readings, taken at least 1-inch from the conditioned surface.

11.2 SAWING AND MACHINING

Titanium pipe joints are generally prepared by either sawing or machining. Both stationary and portable cut-off saws are available for joint preparation. Portable saws require minimal clearance and can be mounted in any position around the pipe. Cermet or carbide tipped saw blades are recommended. If steel saws or abrasive cut-off wheels are used, the joint surfaces *shall* be dressed with carbide burrs or files to remove any embedded or adhering steel particles. This is accomplished by removing all surface markings from the saw cut surface.

Machined joints provide the most accurate joint fit-up and are recommended for titanium pipe welding. Traditionally, titanium has been classified as difficult to machine because the material will work harden, which causes a complete absence of a "built-up edge," ahead of the cutting tool. This results in the formation of a high shearing angle, which causes a thin chip to contact a relatively small area on the cutting tool face. This, in turn, results in a high bearing load per unit area. The high bearing force, combined with the friction developed by the chip as it passes over the bearing area, results in a large increase in heat on a very localized portion of the cutting tool.

The combination of high bearing forces and heat produces cratering action to the cutting edge, resulting in rapid tool breakdown. In addition, titanium has a strong alloying tendency or chemical reactivity with materials in the cutting tool, which causes galling, welding, smearing and

* The Rockwell C scale is designed for high strength titanium alloys and is not applicable to the CP grades used in titanium piping systems. The Rockwell B scale should be used to evaluate the hardness of CP titanium. However, at the time this report was published an acceptance criterion for Rockwell B has not been completed.

rapid destruction of the cutting tool. To overcome the above problems, the following general recommendations have been developed for machining titanium:

- Use low cutting speeds. A change from 20 surface feet per minute to 150 surface feet per minute using carbide tools results in a temperature change from 800° F to 1700° F.
- Maintain high feed rates. Temperature is not affected by feed rate so much as by speed and the highest feed rates consistent with good machining practice should be used.
- Use copious amounts of cutting fluid. In addition to washing away the chips, the coolant provides heat transfer at the cutting edge, which prolongs tool life.
- Use sharp tools and replace them at the first signs of wear. Tool failure occurs quickly after a small amount of wear.
- Never stop feeding while the tool and workpiece are in moving contact. Allowing a tool to dwell in moving contact causes work hardening and promotes smearing, galling, seizing and tool breakdown.
- Use rigid setups. Rigidity of the tool and the workpiece ensures a controlled depth of cut.

While joint details can be prepared using conventional machine shop equipment, it is generally more economical to use pipe end preparation machines. Both stationary and portable end-prep systems are available, and can be used to bevel, face, or groove. Carbide or cermet cutting tools are recommended for both conventional and end-prep machines. If high-speed steel tooling is used, the joint surfaces *shall* be dressed with a carbide burr or file to remove any embedded or adhering steel particles. As with saw cut surfaces, this is accomplished by removing all surface marks from the machining operation.

11.3 SAFETY

The accumulation of titanium fines in machines constitutes a fire hazard. In addition, the concentration of titanium dust or powder of minus 100-mesh in an enclosed area can create an explosive dust-air mixture when subjected to a spark or flame. To ensure a safe work environment, the shipyard/contractor *shall* prepare written procedures for the collection, storage and disposal of titanium chips, filings and dust from machining, cutting and grinding operations. These procedures *shall* be submitted to and approved by NAVSEA prior to production welding of titanium.

A regular clean-up schedule is recommended to prevent the accumulation of titanium chips, turnings, fines in machines or dust in enclosed areas both in the shipyard and shipboard. In the event of a fire, the fire can be extinguished with a National Fire Protection Association Class D extinguisher (sodium chloride based dry powder extinguisher such as MET-L-X) or other chemical-type extinguishers such as DOW 230 Flux. Carbon dioxide and foam extinguishing agents are not effective on titanium fires. Water will promote a violent reaction and should never be used in an attempt to extinguish a titanium fire.

12.0 PRE-WELD CLEANING

Prior to final fit-up and welding, it is essential that the weld joint be free of mill scale, oil and grease from machining and forming operations, dust, dirt, moisture and other potential contaminants. The inclusion of these foreign materials into the weld metal will contaminate and, subsequently, embrittle the weld deposit. Proper surface preparation requires that the entire joint and adjacent base material on both the inside and outside diameters of the pipe for a minimum of 1-inch on either side of the joint be thoroughly cleaned and degreased before welding.

12.1 BASE MATERIALS

Light oxide scale formed on the joint surfaces of the pipe at temperatures up to about 1000° F can be removed by acid pickling. An acceptable pickle bath is 4-wt% hydrofluoric and 40-wt% nitric acid. Dipping of weld joint areas for 1 to 15 minutes (depending on the activity of the bath) should be sufficient. After pickling, the pipe should be rinsed in cold water to remove the acid, followed by a hot water rinse to facilitate drying.

Heavy scale and oxygen contaminated surfaces formed at temperatures above 1000° F are best removed by mechanical methods. To ensure complete removal of the contaminated surface layer, a minimum of 1/32-inch of material *shall* be removed from any forged, cast or heat-treated surface that will be welded over. If metal removal is by grinding, carbide burrs are recommended. Grinding wheels produce residues of rubber or resin on the surface that contaminate the weld. Ground surfaces *shall* be conditioned with tungsten carbide burrs or files. If steel tools are used, the surface *shall* be dressed with carbide burrs or files to remove all surface markings from the cutting operation.

Pipe received from primary fabricators is usually provided in the descaled and pickled condition, and requires only abrasive cleaning and degreasing. Only stainless steel wire wheels and brushes *shall* be permitted for use in cleaning the final titanium joint surfaces. Sandpaper, emery paper and steel wool can leave abrasive particles on the surface, which are sources of contamination, and should never be used on titanium.

The final joint surfaces *shall* be brushed with a stainless steel wire brush and wiped with an approved solvent using a clean lint-free cloth for a minimum of 1-inch on each side of the joint. (A minimum of 2-inches beyond the width of all gas shielding devices is recommended). Solvent degreasing with acetone is recommended, but other solvents such as denatured alcohol or other nonhalogenated solvents are acceptable [8]. Vapor degreasers that contain chlorinated solvents and silicated solvents should never be used, as residuals from these solvents promote weld metal cracking. All residual solvent should be eliminated and the areas inspected for cleanliness prior to fit-up and tack welding.

Subsequent to this degreasing operation, all parts should be handled with clean, dry, cotton gloves. Handprints (i.e. oils from your hand) are a source of contamination. Rubber gloves can leave traces of plasticizer that can act as a source of porosity in the weld and should never be used in handling any titanium part. Re-cleaning is required at any time during the welding cycle if the weld area has been contaminated by dirty tools, gloves, or hands, etc. The

clean joints should be covered with plastic or other type of covering when not being worked on. Tape should not be used to protect the cleaned joints, as it may leave a residue on the groove faces after removal.

12.2 FILLER MATERIALS

Filler materials have a large surface-to-volume ratio. If the spooled wire or rod is slightly contaminated from die lubricants, the weld will be severely contaminated. Although the majority of titanium manufacturers provided spooled wire that have been properly cleaned, an inspection wire test is recommended at the start of each shift or whenever a new wire spool is installed. To perform the inspection test, unwind approximately two feet of wire from the spool. It is not necessary to sever the wire unless its usability is questionable. Using a lint-free industrial tissue or lint-free cloth soaked in acetone, wipe the wire in a back and forth motion 4-5 times. Visually examine the wipe for any evidence of contaminants. A slight darkening or smudge is acceptable. A dark smudge or evidence of flakes or particles from the wire should be cause for rejection and the spool returned to the manufacturer for re-cleaning. For manually fed wire or rod, the electrodes *shall* be wiped with a clean, solvent-soaked cloth prior to initial use and/or re-use and thereafter *shall* be handled only with clean, lint-free cotton gloves.

Personnel using acetone or other approved solvents should wear clean nonporous type gloves while performing cleaning operations. Lint free cloth or lint free industrial tissue used in the cleaning operation should be placed in a metal container with a lid. Exhaust ventilation should also be in operation when using solvents.

13.0 JOINT FIT-UP AND TACKING

After cleaning, the piping components are clamped together for tack welding. Accurate fit-up is more critical for titanium than other materials. Uniform fit-up minimizes burn-through and controls underbead contour. Poor fit-up may increase the possibility of contamination from air trapped in the joint, particularly with thin walled titanium piping. As noted previously, machined joints are recommended to ensure accurate fit-up. Maintenance of the joint alignment is accomplished using the same type of clamping devices as used for other piping materials. The joint edges should meet to form a true square-edge to assure proper inert gas shielding during welding. Perpendicularity of the edges should be maintained within 5 degrees. All clamps and fixtures used on the final joint surfaces *shall* be clean and grease free.

When performing tack welding operations for fit-up, the same care in cleanliness and inert gas shielding *shall* be exercised, as with all titanium welds, to prevent contamination. The use of trailing and back-up shielding is mandatory. Tack welds to be incorporated into the final weld *shall* be visually examined and defects such as cracks and undercut *shall* be corrected to the extent necessary to ensure final weld quality requirements will be met. Cracks in tack welds *shall* be removed and another tack weld made before proceeding. However, it is not necessary to remove cracked or broken tack welds if they were made with the GTAW process, will not cause the joint to exceed fit-up requirements, will be completely re-melted in the first pass and the first pass is made with the GTAW process.

14.0 WELDING PROCEDURE AND TECHNIQUE

14.1 PREHEATING

The minimum required preheat and maximum interpass temperatures for titanium *shall* be 60° and 250° F, respectively. Preheat may be required if the presence of moisture is suspected due to low temperature, high humidity or a wet work area. In such cases, heating of titanium *shall* be limited to the use of lamps, resistance heaters or induction heating equipment. When using resistance heaters or induction coils, contact of the heating elements with the joint surface is prohibited, along with the use of oxy-fuel gas torches. Contact pyrometers *shall* be used for measuring the surface temperature. Temperature indicating crayons *shall not* be used on titanium materials.

14.2 TUNGSTEN ELECTRODE PRACTICE

To ensure adequate torch gas shielding of the electrode, it is recommended that electrode extension beyond the tip of the torch cup does not exceed one and a half times the electrode diameter. As noted previously, electrode extension may be increased to as much as 1-1/2 inches with special large diameter gas lens. However, the effectiveness of the torch and trailing shield gas in cases of increased electrode extension should be verified prior to production welding.

The arc length should also be as short as possible, but with sufficient gap to avoid stubbing out. As a general rule of thumb, the arc length is set about equal to the electrode diameter when welding without filler material. If filler wire is added, the maximum arc length should be about 1-1/2 times the electrode diameter. Longer arc lengths can cause turbulence within the arc, which may draw air into the weld pool. Increasing the arc length also increases the width of the weld. A gap gauge placed between the electrode tip and the surface of the pipe can be used to ensure a consistent arc length.

During welding, the electrode may become oxidized by insufficient gas flow through the torch or shut-off of the torch gas before the electrode has cooled. In addition, contamination of the electrode can occur in manual GTAW, when the welder inadvertently dips the electrode into the weld pool or touches the tungsten with the filler rod. When this occurs, the contaminated section of the electrode should be broken off and re-ground to the previous shape. In the event of electrode contamination of the weld, the contaminated weld metal *shall* be ground out with carbide burrs or files and thoroughly cleaned and inspected prior to re-welding.

14.3 FILLER METAL PRACTICE

When mounting or removing a wire spool from the wire spool hub, the wire *shall* be handled only with clean cotton gloves. Any wire, which has been improperly handled, *shall* be

removed from the spool and discarded. Once mounted on the wire spool hub, the wire *shall* be kept enclosed in a dust cover. As noted previously, manually fed wire or rod *shall* be cleaned with a solvent prior to initial use and/or re-use and thereafter handled only with clean cotton gloves, except for clean leather gloves which may be used in actual welding.

Filler materials should be fed smoothly and continuously into the weld pool. At the completion of the weld pass, 1-inch of the wire or rod *shall* be removed from the tip before re-use. Intermittent dipping of the wire or rod in manual GTAW should never be used in titanium welding, as this technique may result in contamination of the hot end of the wire or rod on removal from the shield. The contaminants are then transferred to the weld puddle on the next dip.

If an extended period of time occurs between the use and reuse of the spooled wire, the wire spool *shall* be removed from the wire spool hub and stored in a clean, dust-free container. Manually fed wire or rod not in use for an extended period *shall* also be place in clean containers. Prior to re-use, the wire or rod *shall* be wipe tested by drawing a solvent soaked cloth along a 12-inch length of the filler material. A slight darkening is acceptable but any evidence of foreign material is cause for rejection until the wire or rod is double-wiped with solvent and passes the wipe test. Lastly, the wire feed path *shall* be cleaned daily to remove any chips or dirt that may accumulate in the guide tube, rollers or torch.

14.4 WELDING PARAMETERS

The exact combination of settings will be determined in welding procedure qualification work. Typical welding parameters for steady current, manual GTAW of square groove (P-1) and socket (P-80) joints in 4-inch diameter, schedule 10S pipe are provided in Table 10 for information.

14.5 INTERPASS CLEANING

At the completion of each pass, do not brush or clean the weld surface. Visual inspection of each pass for surface color *shall* be in the as-deposited condition. A lustrous silver color is acceptable. Straw discoloration on surfaces to be welded over *shall* be removed by stainless steel wire brushes or wheels.* For other colors, welding *shall* be stopped, the shielding problem *shall* be corrected, and the unacceptable area *shall* be repaired and inspected in accordance with the requirements contained in sections 14.6 and 15.0, respectively, before welding is resumed.

Table 10. Welding parameters for manual GTAW of titanium pipe.

Material	Ti-CP, grade 2	Ti-CP, grade 2
Joint	Square Groove (P-1)	Socket (P-80)
Weld	Butt	Fillet
Process	Manual GTAW	Manual GTAW

* For S-53 titanium alloys listed in Table 1 of S9074-AR-GIB-010/278 [8], straw color is removed by carbide burring or filing.

Position	Horizontal		Horizontal	
Layer	Root	Remainder	Root	Remainder
Filler Metal	NA	ERTi 2	ERTi 2	ERTi 2
Filler Metal diameter, in	NA	3/32	0.060	3/32
Electrode Type	2 % thoriated	2 % thoriated	2 % thoriated	2 % thoriated
Electrode Diameter, in	3/32	3/32	3/32	3/32
Voltage, V	10-12	10-12	10-12	10-12
Amperage, amps	135-140	125-130	70-90	90-110
Travel Speed, IPM	5-5.5	6.5-7	4-4.5	4.5-5
Shielding Gas	100 % Argon	100 % Argon	100 % Argon	100 % Argon
Torch Gas, cfh	20	20	20	20
Trailing Shield Gas, cfh	70	70	70	70
Internal Shield Gas, cfh	50	50	45	45
Preheat, ° F	60	60	60	60
Interpass, ° F	250	250	250	250

14.6 WELD REPAIR

Repairs in titanium pipe welds *shall* be made with the same care and workmanship as for the original weld. The removal of defects *shall* be by machining or grinding in accordance with the requirements contained in Section 11.0. Final preparation *shall* be with tungsten carbide burrs, wheels or files, followed by stainless steel wire brushing and acetone degreasing for a minimum of 1-inch on each side of the repair area. The final surface of the repair weld *shall* be inspected for surface color in the as-deposited condition by a qualified visual inspector.

Dye penetrant inspection (PT) *shall* not be used on repair surfaces to be welded over unless a crack is detected by visual examination and then *shall* be used only in the limited area of the crack to confirm its removal. All traces of the penetrant *shall* be removed prior to welding. The PT repair area *shall* be ground with carbide burrs and should be thoroughly cleaned with solvent. Thermal methods *shall not* be used for any type of defect removal or backgouging. If repair welding is not required to meet minimum thickness requirements, the excavation *shall* be blended smoothly into the adjacent material.

Arc strikes and welded attachment removal sites on base materials *shall* be ground to fair smoothly with the adjacent material. If grinding reduces the pipe thickness below design requirements, the area *shall* be restored by welding and grinding. Finish ground areas, whether repair welded or not, *shall* be visually inspected at 5X magnification by qualified production personnel.

15.0 VISUAL INSPECTION

The color of the as-deposited weld can be used as an indicator of shielding effectiveness and, indirectly weld quality. Surface colors reflect the degree to which the weld was exposed to interstitial elements, primarily oxygen, at welding temperatures. The surface color of a properly shielded weld is a bright and lustrous silver color. Pickup of oxygen due to improper shielding or gaseous impurities in the shielding gas thickens the oxide layer, which changes color from light

refraction. The color of the oxide layer changes as a function of increasing oxide thickness from silver to light and dark straw, purple, dark blue, light blue, yellow, dull gray and powder white. Technical publication S9074-AR-GIB-010/278 [8] uses surface color as the acceptance criteria for visual examination of titanium welds and adjacent areas.

The inspection of intermediate weld passes and adjacent material may be performed by production personnel, if they are trained and periodically audited to ensure proficiency in accordance with a program approved by the shipyard's technical publication T9074-AR-GIB-010/271 [10] test examiner. The final surface of the weld and adjacent 1/32-inch of base material beyond the weld toe, all weld repairs, and, when accessible, the backside of the weld surface *shall* be inspected for color by a qualified visual inspector. This inspection is also performed in the as-welded condition.

15.1 ACCEPTANCE STANDARDS

Visual inspection of all weld passes, including the backside of two-sided welds, *shall* be performed in the as-deposited condition, that is, prior to any type of cleaning, brushing or grinding operation. Areas that require inspection for surface discoloration include the outside surface of the weld pass and adjacent 1/32-inch of material, the accessible backside of the weld and adjacent 1/32-inch of material, and base material beyond 1/32-inch from the weld toes. A boroscope is not required for internal inspection of inaccessible backside pipe welds.

The acceptance criteria for color inspection and disposition requirements [8] are provided in Table 11. A bright, shiny silver color on intermediate and final surfaces of the weld and adjacent 1/32-inch of material is acceptable. A straw color on intermediate weld surfaces that will be welded over *shall* be removed by stainless steel wire brushing. A straw color on the final weld surface does not require removal. Other colors (purple, dark blue, light blue,* yellow, gray and white) require complete removal of the weld bead and adjacent 1/16-inch of material. The source of the discoloration, i.e. drafts, gas delivery system, joint cleanliness etc., *shall* be corrected before welding is continued. Re-welding of the final weld surface requires a final visual inspection for color by a qualified VT inspector.

Table 11. Acceptance criteria and disposition for visual inspection.

Color of Weld, Adjacent 1/32-inch of Material and Backside of Weld*	Disposition	
	Intermediate Weld Surfaces	Final Weld Surface

* The disposition of the "very light blue color" in Section 10.4 of technical publication S9074-AR-GIB-010/278 [8] is being revised. This color will be dispositioned in the same manner as with all other colors except straw.

Silver	Acceptable	Acceptable
Straw	Remove by stainless steel wire brushing	Acceptable
All other colors	Remove complete weld bead and 1/16-inch surrounding material	Remove complete weld bead and 1/16-inch surrounding material
*If accessible without the use of a boroscope.		

For base material surfaces beyond 1/32-inch from the weld toes, all colors on material to be welded over *shall* be removed after inspection. A straw color *shall* be removed by stainless steel wire brushing. Other colors *shall* be removed by carbide burring or filing. For base material surfaces beyond 1/32-inch from the weld toes that will not be welded over, all colors, except for straw, *shall* be removed after inspection by carbide burring or filing. This operation may be performed at the completion of welding.

15.2 GENERAL INSPECTION

A general visual inspection *shall* also be performed in accordance with the requirements of T9074-AS-GIB-010/271 [10]. The acceptance criteria for this inspection are provided in MIL-STD 2035 [23]. No cracks or surface porosity is permitted. The weld contour *shall* blend smoothly and gradually into the base material. In the event of grinding, the thickness of the weld and adjacent base material *shall* not be reduced below the minimum design thickness. The degree of undercut, weld reinforcement and root reinforcement is determined by the class of welding [10]. Other inspection requirements *shall* be as dictated for the piping class and joint types shown in Table IX of S9074-AR-GIB-010/278 [8].

16.0 SUMMARY

The mechanical properties of titanium welds are heavily influenced by welding procedure, in particular, the joint cleanliness and adequacy of inert gas shielding during welding. Proper welding procedures must be rigorously observed in order to obtain high quality welds. A summary of the fabrication, welding and inspection requirements is provided in Table 12.

Table 12. Fabrication, welding and inspection requirements for Ti-CP pipe welding.

Area	Requirement	Reference*
Quality Assurance		
General	Prepare written procedures for all inspections and internal audits	Section 4.1.2.1

Receipt Inspection	Perform physical and technical inspections of all incoming materials used in fabrication including shielding gases, cleaning solvents and dye penetrants	Section 4.1.2
	Certify all materials for purity and conformance to specifications and/or fabrication plan	Section 30.2.1
	Maintain records of receipt inspections	Section 30.2.1
	Perform random sampling of received materials	Section 4.1.2
Material Identification	Identify all materials by specification number and grade	Section 4.1.2
	Maintain identification of all materials to the point of initial fabrication	Section 5.3.1
	Visually verify material identification at initial point of fabrication	Section 4.1.2
	Perform periodic audits of inventories, storage facilities and shops for material identification	Section 4.1.2
Material Storage	Store all filler materials in original closed containers until used	Section 6.6.5
	Develop a training plan, including methods to ensure continuous compliance, on material handling and submit to NAVSEA for approval	Section 30.3
	Prepare written procedures for material handling	Section 30.3
	Train and test all personnel working with titanium on handling procedures	Section 30.3
	Maintain records of training and test results	Section 30.3
Records	Maintain signed inspection records for each pipe weld	Section 4.1.3
Welding Qualification	Qualify procedures to Section 4.0 requirements of technical publication S9074-AQ-GIB-010/248 prior to production welding	Section 4.2
	Qualify welders and welding operators to Section 5.0 requirements of technical publication S9074-AQ-GIB-010/248 including Section 5.2.3.1 requirements for training and Section 5.2.12 requirements for color perception testing	Section 4.2
	Train out-of-chamber welders for in-chamber welding	Section 4.3.2
NDT Personnel	Qualify all NDT procedures and personnel to the requirements of technical publication T9074-AS-GIB-010/271	Section 4.5

Table 12. (Continued)

NDT Personnel	Prepare written procedure for color inspection	Section 4.5
	Qualify VT inspectors for color inspection including color perception test on workmanship samples	Section 4.5

Fabrication Plan	Prepare a fabrication plan including fabrication design, workmanship and inspection standards, forming and heat treating procedures and safety procedures and submit to NAVSEA for approval prior to fabrication welding	Section 30.1
	Obtain NAVSEA approval of fabrication plan prior to production welding	Section 30.1
Materials		
Base Materials	Conform to ASTM grades 1, 2, 3 and 7	Section 5.2
Filler Materials	Conform to AWS classifications ER Ti-1, -2, -3 and -7	Section 5.2
	Test each lot of filler material to Schedule J of AWS A5.01	Section 5.2
Pipe Bending	Clean all tooling used on the final surface including bending dies and mandrels of grease, oil and metallic contaminants prior to use on titanium	Section 30.2.1.4
Welding Area		
General	Prepare written facility procedure and submit to NAVSEA for approval prior to production welding	Section 30.2
Shipyards	Design all welds to maximize welding in a dedicated shipyard facility	Section 30.1
	Restrict work area from general traffic and protect from winds and drafts	Section 30.2
	Isolate work area from dirt, smoke, and residues from grinding operations being done on other materials	Section 30.2
	Clean and wipe down all equipment brought into welding area	Section 30.2
	Establish regular clean-up schedule that uses vacuum devices exhausting outside of the work area	Section 30.2
Shipboard	Design all welds for accessibility, inert gas shielding and environmental control	Section 30.1
Tools	Dedicate all tools used on the final surface such as carbide burrs and files and stainless steel brushes for titanium use only.	Section 30.2.1.4
	Do not use compressed air for pneumatic tools or blow cleaning of weld joints	Section 30.2
Gas Shielding		
General	Use only argon, helium or argon/helium gas mixtures for welding or furnace purging during vacuum heat treatment	Section 30.2.1

Table 12. (Continued)

General	Use only shielding and purging gases with a gas purity of 99.995% minimum and a dewpoint of -60° F or less at the workpiece or purge exit	Section 30.2.1
	Maintain inert gas shielding until the completion of welding	Section 6.2.7.1

Back Shielding	Shield the backside of the joint with inert gas unless the backside temperature remains below 500° F	Section 6.7.2.1
	To eliminate backside shielding, fabricate a mock-up and submit a description and test temperature results to NAVSEA for review and approval prior to fabrication welding	Section 6.7.2.1
Dewpoint Measurements	Measure dewpoint of the torch gas, trailing shield gas and purge gas at the workpiece or purge exit	Section 30.2.1.1
	Perform dewpoint measurements at the beginning of each worker shift or whenever the gas flow is interrupted	Section 30.2.1.1
	Measure the dewpoint of shielding and purge gases for each weld and weld repair that is not inspected on the backside because of inaccessibility	Section 30.2.1.1
	Obtain dewpoint of -60° F or less prior to welding	Section 30.2.1
Joint Design		
General	Design weld joints for piping in accordance with the requirements of MIL-STD-22	Section 9.2
Joint Preparation		
Thermal Cutting	Remove 1/8-inch of material beyond the kerf from the cut surfaces by sawing, machining, or carbide burring.	Section 11.3.1
	If steel tools are used, dress the thermal cut surface with carbide burrs or files to remove all surface markings from the cutting operation	Section 7.7.2
	Visually inspect the thermal cut surface at 5X magnification to ensure the complete removal of surface cracks	Section 11.3.1
	Perform hardness tests on thermal cut surfaces to verify complete removal of contaminated layer	Section 10.6
Sawing	If steel saw blades are used, dress the joint surfaces with carbide burrs or files to remove all surface markings from the sawing operation	Section 7.2.2
Machining	If steel tools are used, dress the joint surfaces with carbide burrs or files to remove all surface markings from the machining operation	Section 7.2.2
Pre-Weld Cleaning		
Base Materials	Remove 1/32-inch of material from forged, cast or heat treated surfaces that will be welded over. If steel tools or grinding wheels are used, condition the joint surfaces by carbide burring to remove all surface markings	Section 7.7.2
	Use only stainless steel wire brushes and wheels for cleaning the final weld joint surfaces	Section 7.2.2

Table 12. (Continued)

Base Materials	Ensure that all stainless steel wire wheels and brushes are free of any contaminant prior to initial use	Section 30.2.1.2
	Brush final weld joint surfaces with stainless steel wire brush and wipe with approved solvent for a minimum of 1-inch on each side of the joint	Section 7.2.2
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Table 12. (Continued)

Base Materials	Ensure that all stainless steel wire wheels and brushes are free of any contaminant prior to initial use	Section 30.2.1.2
	Brush final weld joint surfaces with stainless steel wire brush and wipe with approved solvent for a minimum of 1-inch on each side of the joint	Section 7.2.2
	Use only acetone, alcohol Formula 23, isopropyl alcohol or other approved solvent for cleaning joint surfaces and adjacent surfaces	Section 30.2.1.2
Filler Materials	Wipe manually fed wire or rod with clean solvent soaked cloth and thereafter handle only with clean, cotton gloves	Section 6.6.5
Joint Fit-Up and Tacking		
Tack Welding	Clean all clamps and fixtures used on the final joint surfaces	Section 30.2
	Use complete inert gas shielding to prevent atmospheric contamination	Section 6.2
	Visually examine tack welds for defects and correct to the extent necessary to ensure weld quality requirements will be met	Section 10.3.8
Welding		
Preheat	Use a minimum preheat of 60° F and a maximum interpass temperature of 250° F	Section 6.3
	Use lamps, resistance heaters or induction heaters only, oxy-fuel gas torches are prohibited	Section 6.3.1.1
	Use only contact pyrometers to measure surface temperatures	Section 6.3.2
	Temperature indicating crayons are prohibited	Section 6.3.2
Filler Material	Handle all wire spools and manually fed wire and rod with clean, cotton gloves, except for leather which may be used for actual welding	Section 6.6.5
	Enclose the wire spool in a dust cover	Section 6.6.5
	Clean the wire feed path on a daily basis	Section 6.6.5
	Clean manually fed wire or rod with a solvent-soaked cloth before use and thereafter handle only with clean gloves	Section 6.6.5
	Remove 1-inch of wire or rod at the completion of each weld pass	Section 30.2
	If an extended period of time elapses before reuse, remove wire spool and store in a clean, dust free container	Section 6.6.5
	If an extended period of time elapses before reuse, store manually fed wire and rod in a clean, dust free container	Section 6.6.5
	Prior to re-use, wipe test the wire or rod along a 12-inch length with a solvent soaked cloth, rejecting any material that shows evidence of foreign material	Section 6.6.5

Table 12. (Continued)

Interpass Cleaning	Do not brush or clean the weld surface at the completion of each weld pass before visual inspection	Section 7.10.2
	Remove discoloration after visual inspection with carbide burrs and files, and stainless steel wire brushes and wheels	Section 7.2.3
	Correct the source of discoloration prior to further welding	Section 7.2.3
Weld Repairs	Do not use thermal methods for any type of defect removal or backgouging	Section 7.10.1
	Use carbide burrs or files for final preparation of the repair area.	Section 7.2.3
	Brush the final surfaces with stainless wire brushes and degrease with approved solvent, along with 1-inch of adjacent material	Section 7.2.3
	If repair welding is not required to meet minimum thickness requirements, blend the repair area smoothly into the adjacent material	Section 7.9
	Grind arc strikes and welded attachments smoothly into adjacent base material and Inspect finish ground areas with VT at 5X magnification by qualified personnel	Section 10.3.5.1
	Do not use PT on material to be welded over unless a crack is detected by VT and then only in the limited area of the excavation	Section 10.4.1
	Grind PT inspected areas with carbide burrs prior to re-welding	Section 13.2.8.1
Visual Inspection		
General	Inspect each weld pass for color, including the backside of two-side welds, in the as-deposited condition	Section 7.10.2
	Inspect the final surface of all welds, including the accessible backside, and all weld repairs for surface color by a qualified VT inspector	Section 10.3.13
Color Acceptance Standards	For intermediate weld surfaces and adjacent 1/32-inch of material, remove straw color on material to be welded over by stainless steel wire brushing	Section 10.4.1
	For intermediate and final weld surfaces and adjacent 1/32-inch of material, remove all colors except for straw by the complete removal of the weld and adjacent 1/16-inch of material	Section 10.4.1
	For material beyond 1/32-inch from the weld toes, remove straw color on material to be welded over by stainless steel wire brushing	Section 10.4.1
	For material beyond 1/32-inch from the weld toes, remove all colors (except straw) on material to be welded over by carbide burring or filing	Section 10.4.1
	After correction of discoloration, inspect final re-welded surface by qualified VT inspector	Section 10.4.1.2

Table 12. (Continued)

General Visual Inspection	Perform general visual inspection in accordance with requirements of technical publication T9074-AS-GIB-010/271	Section 10.3.2
Other Inspections		
General	Perform other inspections as dictated for the piping class in Table IX of technical publication S9074-AR-GIB-010/278	Section 10.3.2
Production Testing		
General	Prepare written procedure for coupon testing	Section 40.2
General	Prepare and test pipe coupons for each qualified welder and welding operator	Section 40.2.1
*Technical publication S9074-AR-GIB-010/278		

controls for ensuring the quality and integrity of the fabricated product. This fabrication plan describes the procedures for fabricating Ti-CP, grade 2 titanium pipe, along with a facility procedure as required by Section 30.2, a training plan as required by Section 30.3, and production testing of weld as required by Section 40.2.

2.0 Responsibilities

2.1 Purchasing Department:

2.1.1 Shall ensure that purchase orders require material certification.

2.2 Material Control Department:

2.2.1 Shall ensure that incoming material complies with the purchase order.

2.2.2 Shall ensure that titanium materials are segregated from non-titanium materials.

2.3 Quality Assurance Department:

2.3.1 Shall ensure that incoming material complies with the requirements of the procurement specifications.

2.3.2 Shall train and certify inspectors for visual inspection of titanium welds

2.4 Design Department:

2.4.1 Shall ensure that location of welds, assembly of subcomponents, etc. is such that all welding is performed in the shipyard facility to the maximum extent possible, and that shipboard welding is minimized.

2.4.2 Shall ensure that the location of all shipboard welds affords good welder accessibility, and that consideration is given to purging access, obtaining requisite fit-up, practicality of establishing temporary areas for cleanliness and all other requirements of this document.

2.5 Training Department:

2.5.1 Shall provide formal instruction to all personnel, within the limits of their discipline, that work with titanium on the requirements of this document, including procedures for handling titanium to avoid inadvertent contamination and to obtain the highest quality product. Included are supervisors and workers in the following areas/crafts; material handlers, machinists, pipe fitters, grinders, welders, VT inspectors, NDT inspectors, designers, engineers and QA auditors.

2.5.1.1 Compliance with this training requirement shall be ensured by a daily check by supervisory personnel or quality assurance. When required, additional training will be identified, provided and documented.

2.5.2 Shall maintain records of personnel training.

3.0 Materials

3.1 Shielding and purge gases shall be argon, helium or mixtures thereof. All shielding and purge gases shall have purity of 99.995% and a dewpoint of -60° F or less.

3.2 Stainless steel wire brushes shall be free of contaminants and shall be used only on titanium and titanium alloys.

3.3 The cleaning solvent used shall be acetone, alcohol formula 23A, and isopropyl alcohol. Other nonhalogenated solvents may be used if proven to have no adverse effect on titanium as determined by Welding Department supervisors.

4.0 Facilities

4.1 The welding area shall be restricted from general traffic, and protected from winds and drafts, dirt, smoke, grinding residues, welding and machining operations on other materials, and other airborne contaminants.

4.2 All equipment to be used in the titanium work area shall be blown clean and wiped down to remove accumulated dust and dirt before being brought into that area.

4.3 The work area shall be cleaned on a regular schedule. Cleaning shall include the use of vacuum cleaners exhausting outside the work area.

4.4 Compressed air, either for pneumatic tools or blow cleaning of weld joints shall not be permitted in the welding area. Argon is recommended for blow-cleaning titanium weld joints.

4.5 Whenever practical, the shipyard facility work requirements shall be applied for shipboard welding as determined by the Welding Engineering Department.

4.6 A checklist of required work area cleanliness, material cleanliness and shielding gas purity shall be filled out prior to the start of each fabrication shift, Table A-1.

Table A-1. Facility checklist.

Item	Data	Welder Signature	Supervisor Signature
Ventilation: Air conditioners in operation Dehumidifiers in operation			
Facility clean and ready for welding: Vacuumed floor			

All debris has been removed			
Facility temperature			
Tooling cleaned			
Filler wire removed from clean/dry storage			
Dewpoint measurements taken: Torch Purge outlet			
Weld wire cleaned			
Weld joint surfaces cleaned			
Wear white cotton gloves			

5.0 Tooling

5.1 All tooling used on the final surface, such as bending dies and mandrels, machine carbide bits, carbide grinding burrs and files, etc. shall be used only for titanium, and shall be stored and maintained so they do not pick up grease, oil or other contaminants.

5.2 Only stainless steel wire brushes and wire wheels, and tungsten carbide burrs, cutters and files are permitted for use on the final weld joint surfaces. All such tools shall be thoroughly degreased with acetone, alcohol formula 23, or isopropyl alcohol before initial use.

6.0 Shielding

6.1 All shielding and purge gases shall have a purity of 99.995% and a dewpoint of -60° F or less at the work piece or purge exit.

6.2 All gas hoses for welding shall be new or shall have been used to carry inert welding shielding gas only.

6.3 Dewpoint of shielding (torch and trailing) and purge gases shall be tested at the beginning of each shift or whenever the gas flow is interrupted, except as follows: dewpoint shall be checked for each weld and weld repair that is not inspected on the backside because of inaccessibility.

7.0 Joint Preparation

7.1 If steel saws or abrasive cut-off wheels are used, the joint surfaces shall be dressed with tungsten carbide burrs or files to remove any embedded or adhering steel particles. This shall be accomplished by removing all surface markings from the cut surface.

8.0 Pre-Weld Cleaning

8.1 Only stainless steel wire wheels and brushes shall be permitted for cleaning the final titanium joint surfaces. Sandpaper and steel wool can leave abrasive particles on the surface, which are sources of contamination, and should never be used.

8.2 The final joint surfaces shall be brushed with a stainless steel wire brush and wiped with an approved solvent using a clean lint-free cloth for a minimum of 1-inch on each side of the joint.

8.3 All cleaned parts shall be handled with clean, cotton gloves.

8.4 Manually fed wire or rod shall be wiped with a clean, solvent-soaked cloth prior to initial use and/or re-use and thereafter handled only with clean, lint-free cotton gloves.

9.0 Welding

9.1 The minimum required preheat and maximum interpass temperatures for titanium shall be 60° and 250° F, respectively. Preheat may be required if the presence of moisture is suspected due to low temperature, high humidity or a wet work area. In such cases, heating of titanium is limited to the use of lamps, resistance heaters or induction heating equipment. When using resistance heaters or induction coils, contact of the heating elements with the joint shall be prohibited, along with the use of oxy-fuel gas torches. Contact pyrometers shall be used measuring the surface temperature. The use of temperature indicating crayons is prohibited.

9.2 When mounting or removing a wire spool from the wire spool hub, the wire shall be handled only with clean cotton gloves. Any wire, which has been improperly handled, shall be removed from the spool and discarded. Once mounted on the wire spool hub, the wire shall be kept enclosed in a dust cover.

9.3 At the completion of each weld pass, 1-inch of the spooled wire or rod shall be removed from the tip before the next pass. If an extended period of time occurs between the use and reuse of the spooled wire, the wire spool shall be removed from the wire spool hub and stored in a clean, dust-free container. Manually fed wire or rod not in use for an extended period shall be placed in clean containers. Prior to re-use, this spooled wire or rod shall be wipe tested by drawing a solvent soaked cloth along a 12-inch length of the filler material. A slight darkening is acceptable but any evidence of foreign material is cause for rejection until the wire or rod is double-wiped with solvent and passes the wipe test.

9.4 The wire feed path shall be cleaned daily to remove any chips or dirt that may accumulate

in the guide tube, rollers or torch.

10.0 Weld Repair

10.1 Repairs in titanium pipe welds shall be made with the same care and workmanship as for the original weld. The removal of defective material shall be by machining or grinding. Final preparation shall be with carbide tooling, followed by stainless steel wire brushing and acetone degreasing. Thermal methods are not permitted for any type of defect removal or backgouging.

10.2 Arc strikes and welded attachment removal sites shall be ground to fair smoothly into base material surfaces. If grinding reduces the pipe thickness below design requirements, the area shall be restored by welding and grinding. Finish ground areas, whether repair welded or not, shall be visually inspected at 5X magnification.

11.0 Inspection

11.1 Each weld pass, including the backside of two sided welds, shall be visually inspected for color in the as-deposited condition, that is, prior to any type of cleaning, brushing or grinding operation. Any indication of mechanical cleaning prior to inspection shall be cause for rejection.

11.1.1 Areas that require inspection for surface discoloration include the surface of the weld pass, adjacent 1/32-inch of base material, and accessible backside. A boroscope is not required for internal inspection of inaccessible backside pipe welds.

11.1.2 The inspection of intermediate passes may be performed by production personnel, if they are trained and periodically audited to ensure proficiency in accordance with a program approved by the shipyard's technical publication T9074-AS-GIB-010/271[10] test examiner.

11.1.3 The final surface of the weld and adjacent 1/32-inch of base material beyond the weld toe, all weld repairs, and, when accessible, the backside of the weld surface shall be inspected for color by a qualified visual inspector. This inspection is also performed in the as-welded condition.

11.2 Welds and surrounding 1/32-inch of material shall exhibit a bright, shiny silver color. A straw color on intermediate weld surfaces that will be welded over may be removed by stainless steel wire brushing, grinding with carbide burrs or filing with carbide burrs. A straw color on the final weld surface does not require removal. All other colors (purple, blue, yellow, gray and white) shall require complete removal of the weld bead and adjacent 1/16-inch of material.

11.2.1 The source of the discoloration, i.e. drafts, gas delivery system, joint cleanliness etc., shall be corrected before welding is continued. Re-welding of the final weld surface shall require a final visual inspection for color by the VT inspector.

11.3 For base material surfaces beyond 1/32-inch from the weld toes, colors other than straw on material to be welded over shall be removed after inspection. For surfaces that will not be welded over, removal of discoloration may be performed at the completion of welding.

11.4 A general visual inspection of the completed weld shall be performed in accordance with the requirements of technical publication T9074-AS-GIB-010/271[10] and shall meet the Class 2 acceptance criteria of MIL-STD 2035.

12.0 Safety

12.1 A regular clean-up schedule shall be used to prevent the accumulation of titanium chips, turnings, fines in machines or dust in enclosed areas.

12.2 Titanium chips, turnings, and fines shall be segregated by storage in noncombustible drums or bins.

12.3 Portable fire extinguishers of Type D shall be used in the event of a fire.

13.0 Production Testing

13.1 Each qualified titanium pipe welder shall prepare a pipe test coupon for visual inspection and bend testing at a bend radius of 2T. The coupon shall be welded in the production environment using the production welding procedure. The coupon shall be completed at intervals of not less than 60 days and not more than 92 days. A written procedure for coupon testing shall be prepared by the shipyard and records shall be maintained for each welder for the preceding 12 months.

13.2 If the coupon fails, the cause of the failure shall be determined and corrected, and the welder shall be permitted to repeat the test coupon once. Failure of a second coupon terminates all the welder's qualifications for titanium and full re-qualification is required. If failure is due to a weld defect only, one bend specimen failure per test is permitted provided two additional bend specimens of the same type are removed from the coupon and are satisfactorily tested per technical publication Technical Publication S9074-AR-GIB-010/248 [9].

APPENDIX B - TITANIUM SUPPLIERS AND SERVICES

The following is a selected list of manufacturers, suppliers and products used in titanium pipe welding. It is noted that this list is neither an endorsement of a product nor a recommendation of a specific manufacturer. Additional information about these products can be obtained in either of the following publications:

- "Products and Services," Thomas Register, latest year.
- "Buyer's Guide," International Titanium Association, Boulder CO

Table B-1. Selected listing of titanium suppliers and services.

Product	Supplier
MATERIALS	
Piping	TIMET, 1999 Broadway, Suite 4300, Denver, CO 80202 303-296-5600
	RMI Titanium Company, 1000 Warren Avenue, P.O. box 269, Niles, OH 44446 330-544-7622
	Dynamet Incorporated, 195 Museum Road, Washington, PA 15301 412-228-1000
	AstroCosmos Metallurgical, 3225 West Old Lincoln Way, Wooster, Ohio 44691 330-264-8639
Filler Materials	AstroCosmos Metallurgical, 3225 Lincoln Way West, Wooster, Ohio 44691 330-264-8639
	Ti Wire Corporation, Morea Road, Frackville, PA 17931 717-874-0311
WELDING EQUIPMENT	
TIG Torches	CK Worldwide, Inc., 3501 C Street. N.E., Auburn, WA, 98002 800-426-0877
	Weldcraft, 119 East Graham Place, Burbank, CA 91502 800-946-2281
Electrode Grinders	Pro-Fusion Inc., 1090 Lawrence Drive, #104, Newbury Park, CA, 91320 805-376-0619
	Diamond Ground Products, Inc., 2550 Azurite Circle, Newbury Park, CA, 91320 805-498-3837
	Intercon Enterprises Inc, C2-1122 Fir Avenue, Blaine, WA 98230 604-946-6066
Gas Purging Units	Intercon Enterprises Inc, C2-1122 Fir Avenue, Blaine, WA 98230 604-946-6066
Dewpoint Meters	Cosa Instrument Corporation, 70 Oak Street, Norwood, NJ 07648 201-767-6600 (Shaw Automatic Dew Point Meter is recommended)
	General Eastern, 50 Hunt Street. Watertown, MA 02172 800-225-3208

Table B-1. (Continued)

Oxygen Meters	Intercon Enterprises Inc, C2-1122 Fir Avenue, Blaine, WA 98230 604-946-6066 (Intercon Oxygen Indicator is recommended)
	Delta F Corporation, 4 Constitution Way, Woburn, MA 01801 617-935-6536 (Delta F Oxygen Analyzer is recommended)
Orbital Pipe Systems	Magatech, Bradley park, PO Box 260, East Granby, CT, 06026 860-653-2573
JOINT PREPARATION	
Pipe Beveling Machines	E.H. Wachs Company, 100 Shepard St., Wheeling, IL 60090 800-323-8185
	H&M Pipe beveling machine Co. Inc., 311 East third St., Tulsa, OK 74120-2417 918-582-9984

Saw Blades	Tru-Cut Saw Inc., 2903 Interstate Parkway, Brunswick, Ohio 44212 330-225-4090
INSPECTION	
Hardness Testers	Equotip Associates, PO Box 1145, 936 maple St., Edmonds, WA, 98020 425771-1292

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